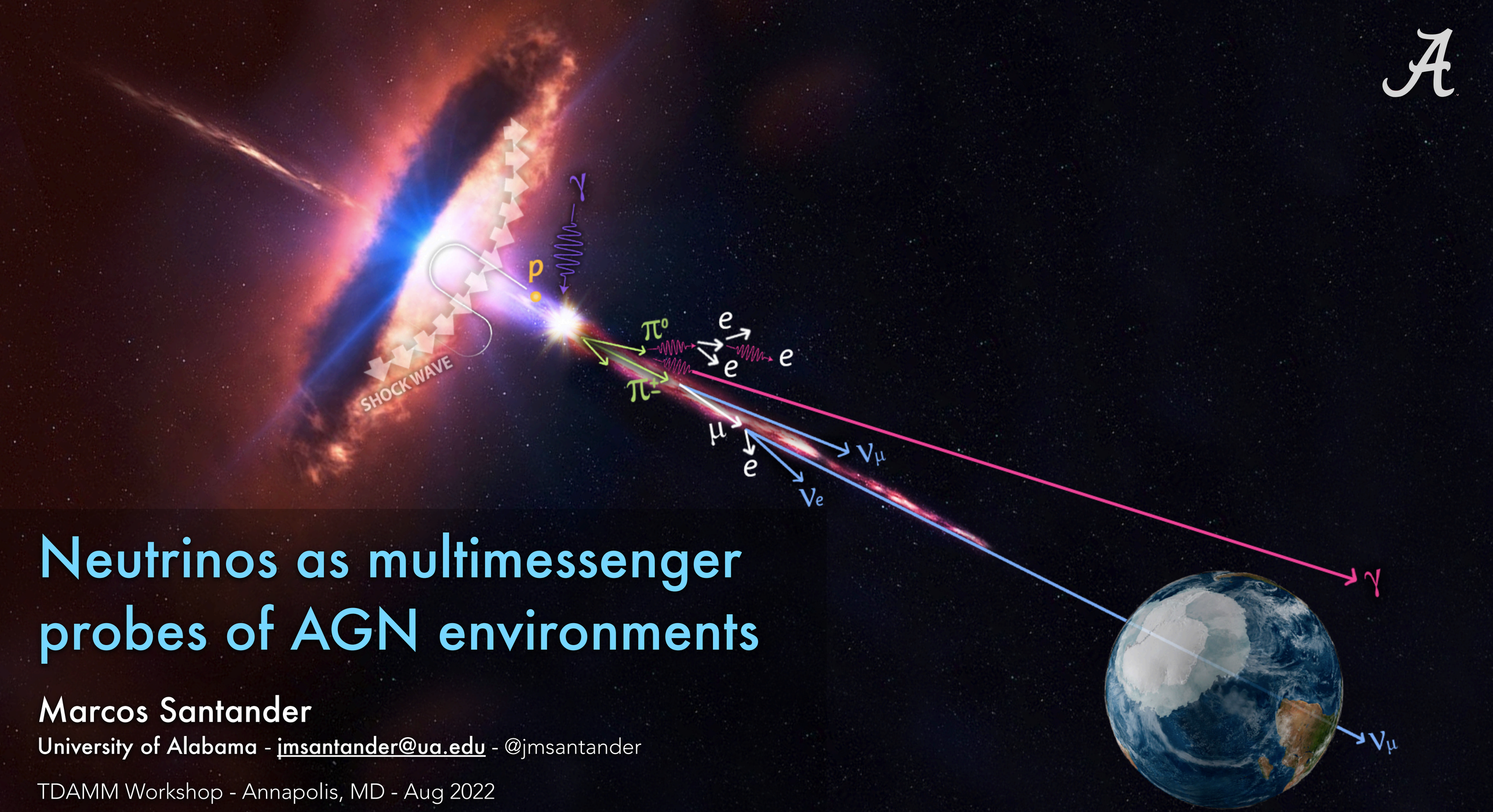


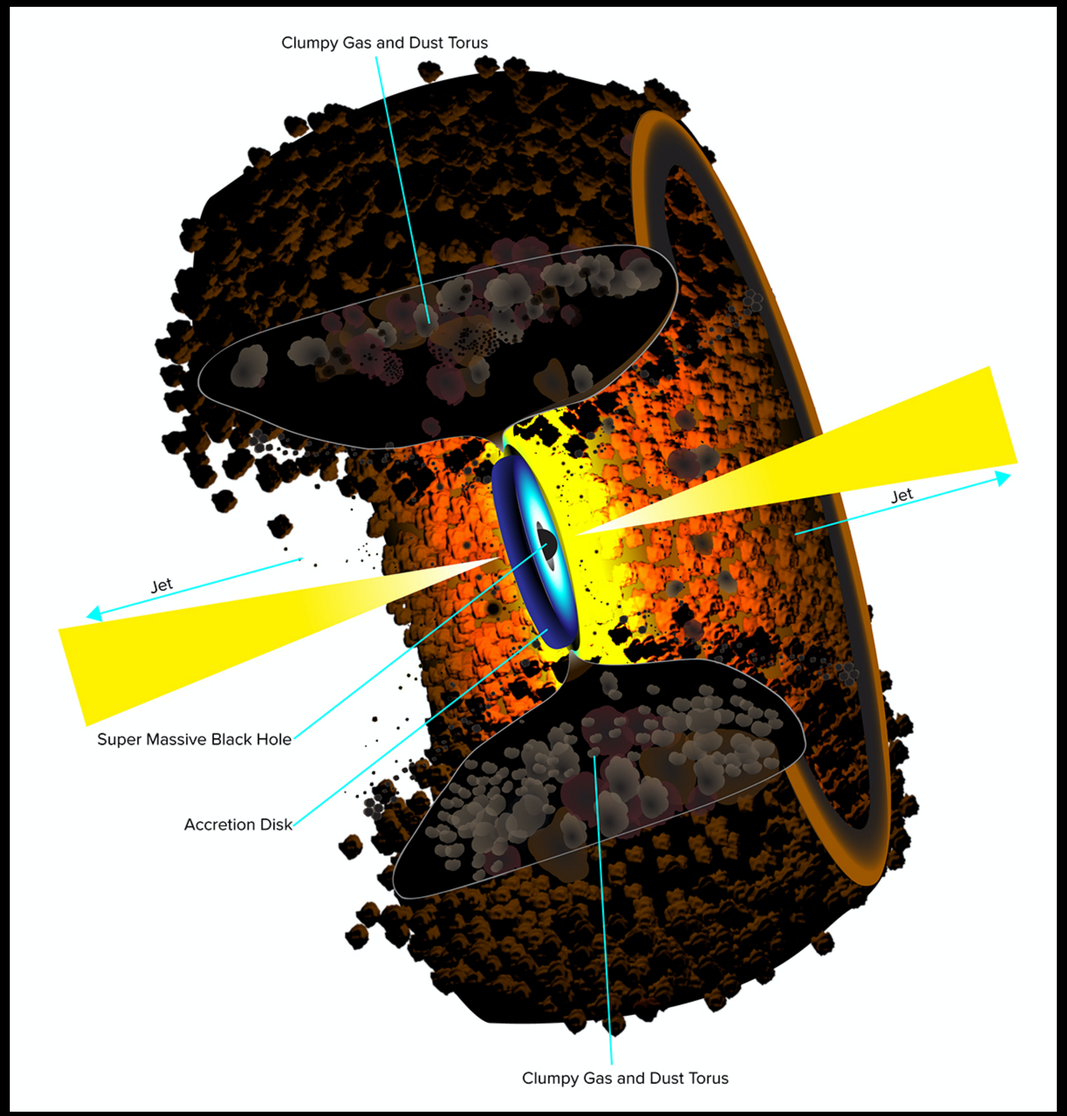
Neutrinos as multimessenger probes of AGN environments

Marcos Santander

University of Alabama - jmsantander@ua.edu - @jmsantander

TDAMM Workshop - Annapolis, MD - Aug 2022

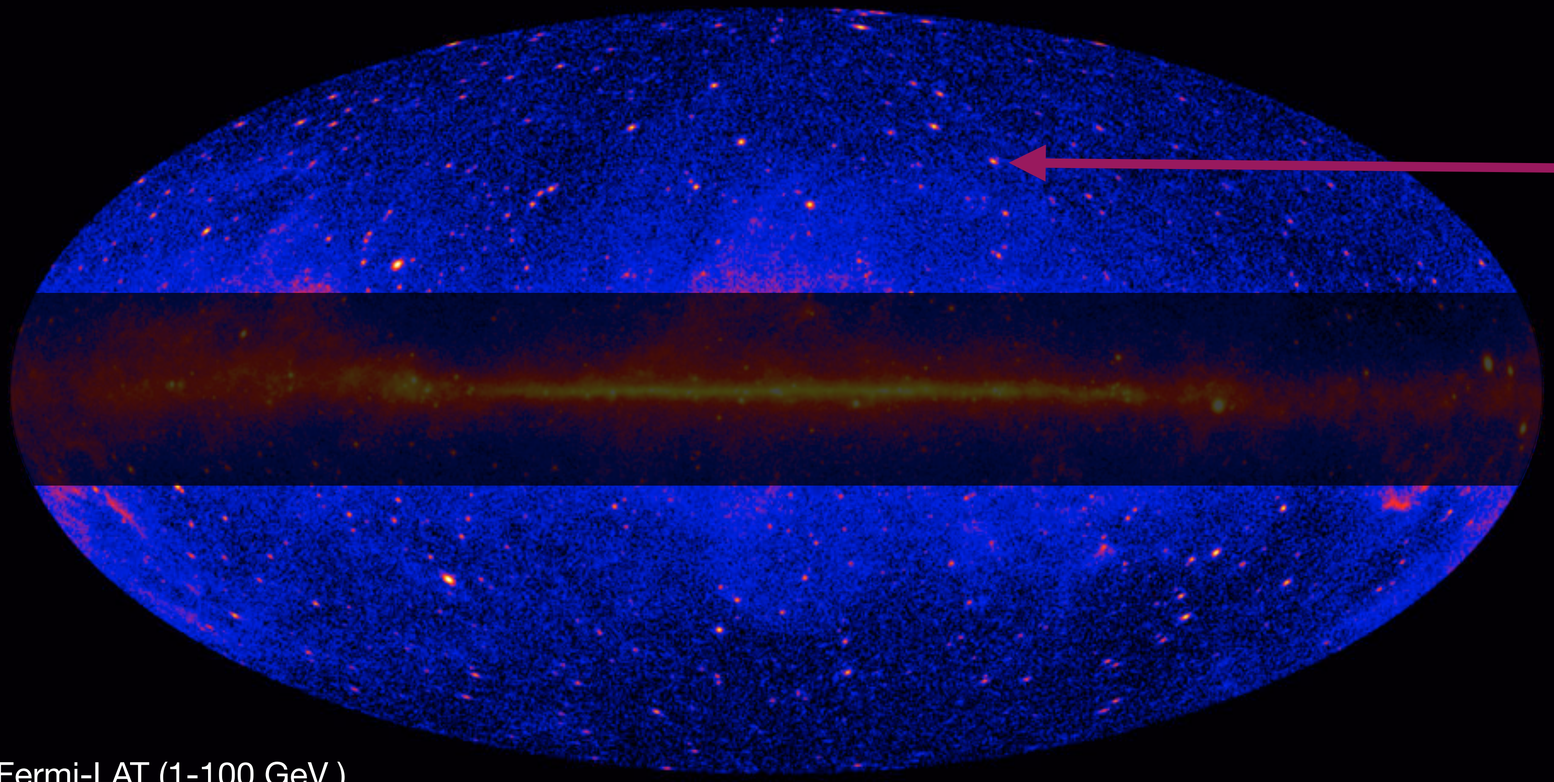
ACTIVE GALACTIC NUCLEI



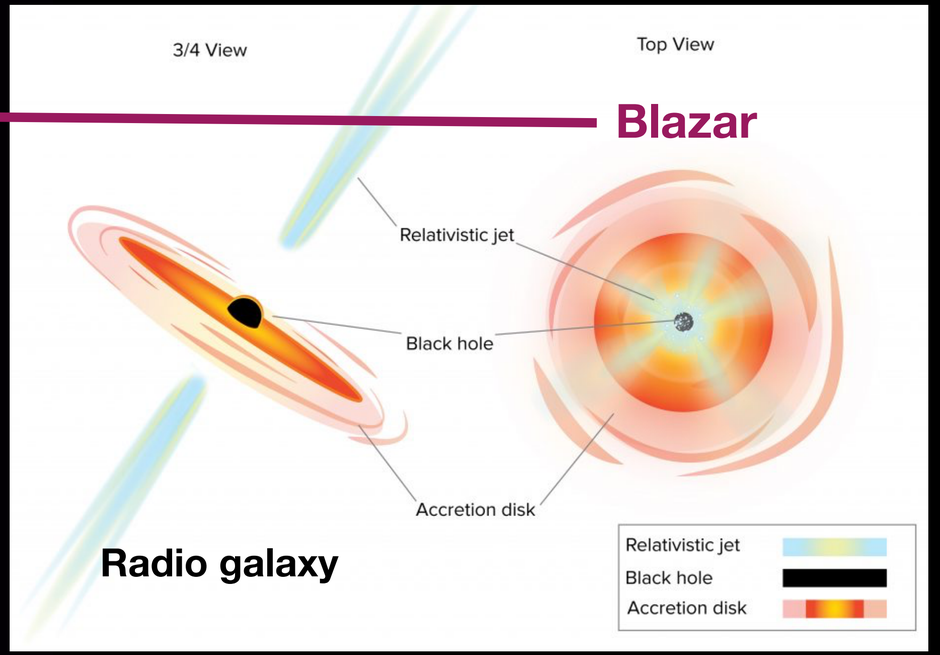
B. Saxton NRAO/AUI/NSF

- Active Galactic Nuclei (**AGN**) powered by accretion into a supermassive black hole (SMBH) are the most luminous persistent sources of EM radiation (typical $L_{bol} \sim 10^{43}$ - 10^{48} erg/s).
- A fraction of AGN display long **relativistic jets**, which dominate the high-luminosity end of AGN distribution. Their emission is observed across the EM spectrum.
- Studying the extreme processes near SMBHs requires observations at the **highest attainable energies.**

EXTRAGALACTIC GAMMA-RAY SKY



Fermi-LAT (1-100 GeV)

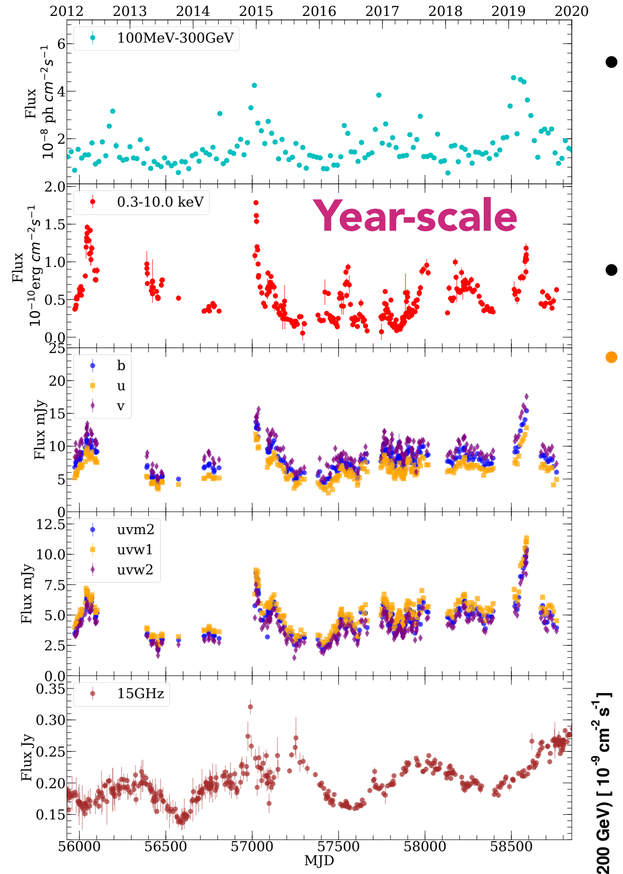


- **Blazars** (face-on jetted AGN) dominate the extragalactic sky at the highest energies (GeV to >TeV gamma rays).

TDAMM

TDAMM

TIME DOMAIN



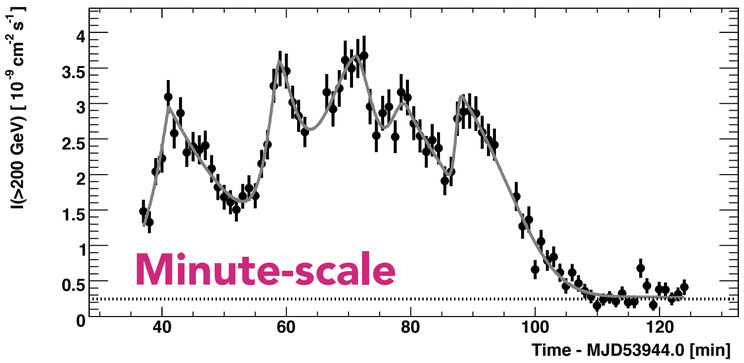
PG 1553+113

S. Huang et al. ApJ 2021, 922, 222
arXiv/2110.01769

- Variable across multiple timescales, from **years** to **minutes**.
- Variability increases with energy.
- **Questions: location, geometry and evolution of the emission region/s.**

PKS 2155-304

F. Aharonian et al. (H.E.S.S.) ApJL 2007, 664, 71
arXiv/0706.0797



TDAMM

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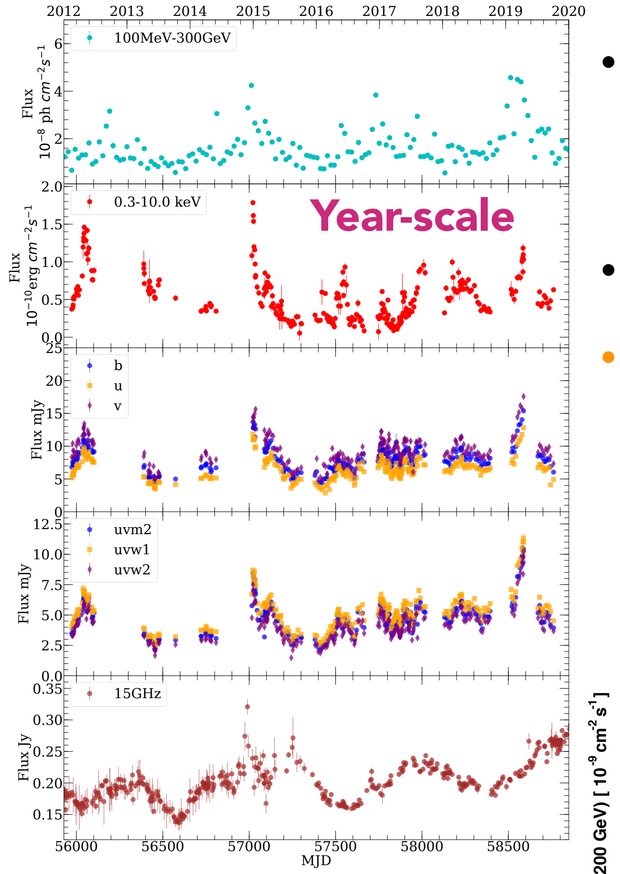

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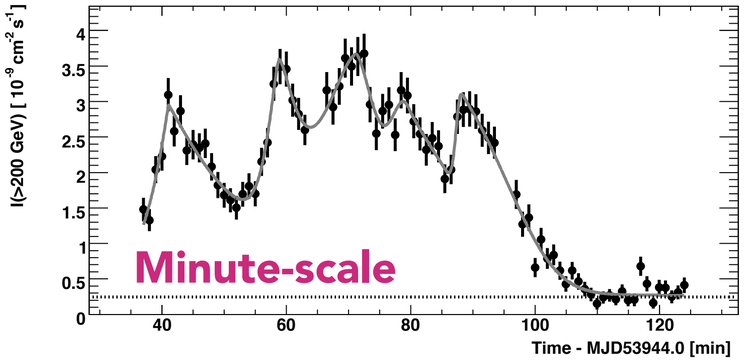
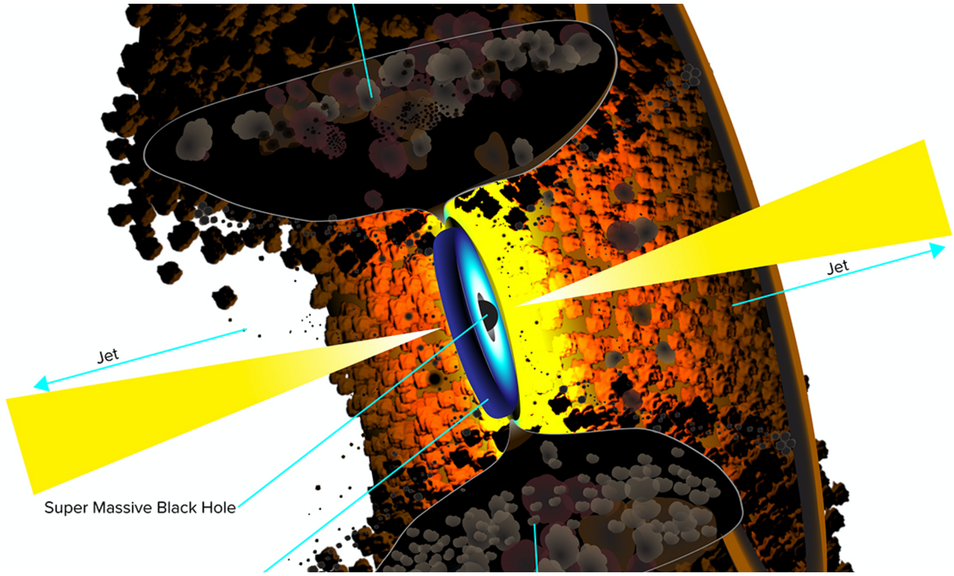
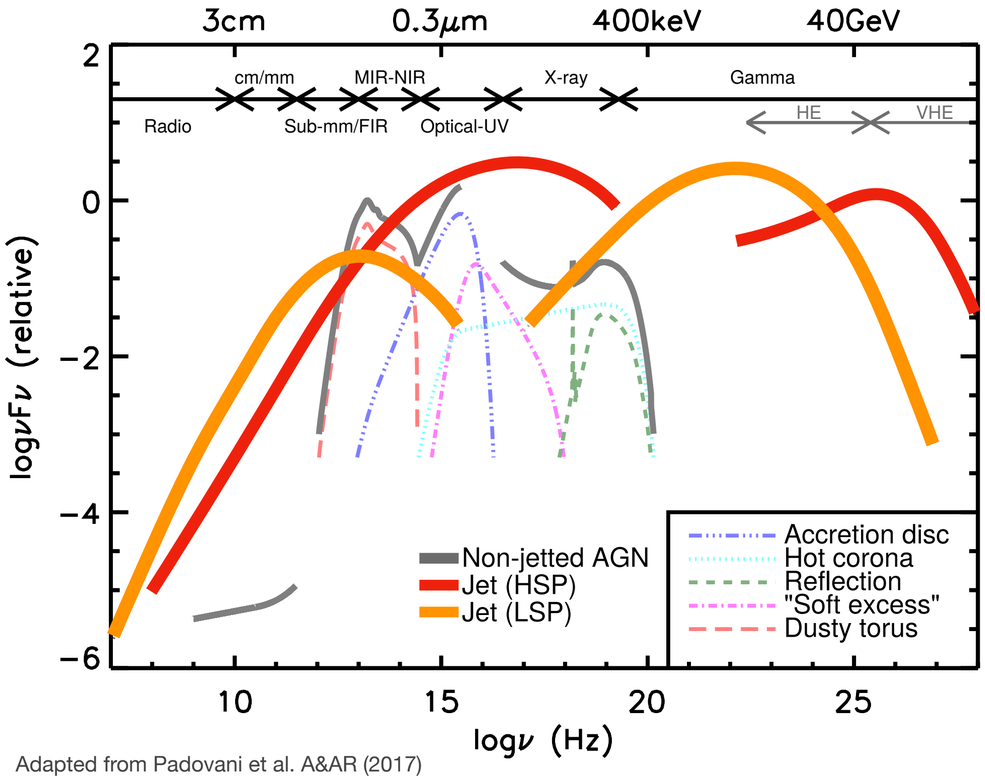


MULTIMESSENGER



- Particle acceleration (and interactions) in the AGN core or in the jet may lead to multimessenger emission: cosmic rays, neutrinos, and hadronic photons.
- **Questions: particle acceleration, origin of HE AGN emission, cosmic-ray and neutrino sources.**

SPECTRAL ENERGY DISTRIBUTIONS OF BLAZARS



Adapted from Padovani et al. A&AR (2017)

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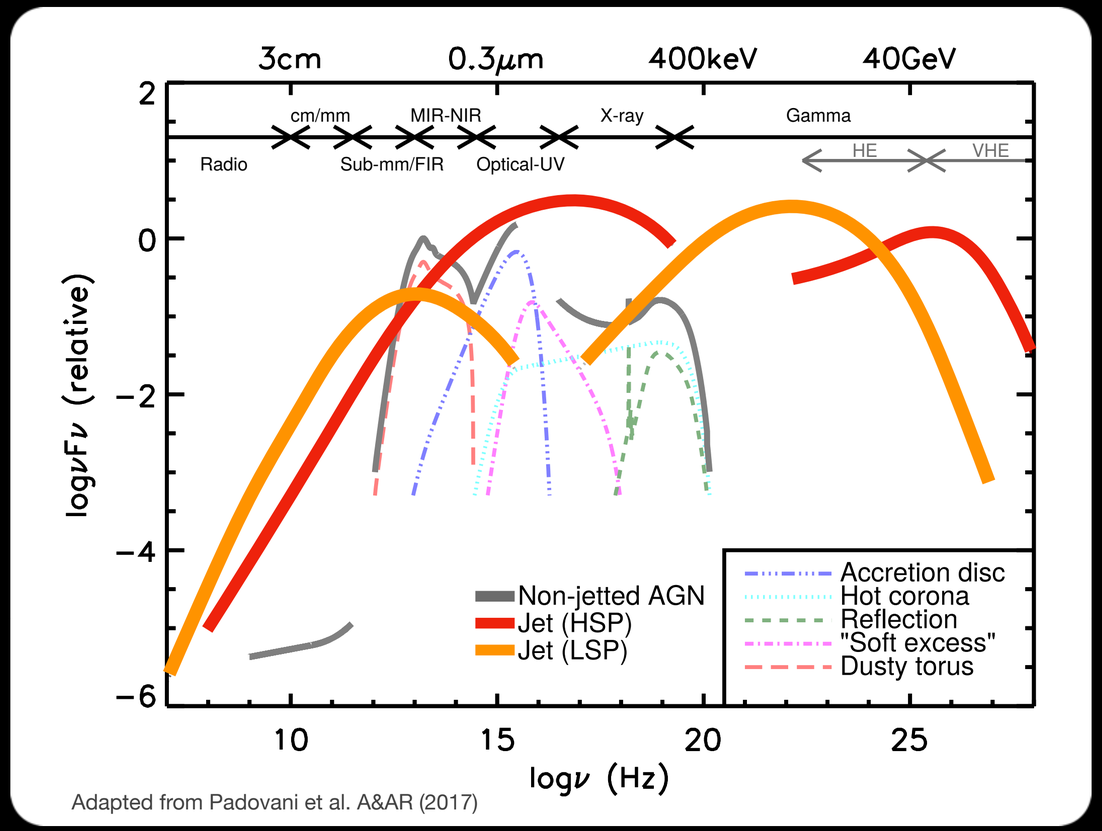

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- Broadband SED characterized by two broad emission "bumps"

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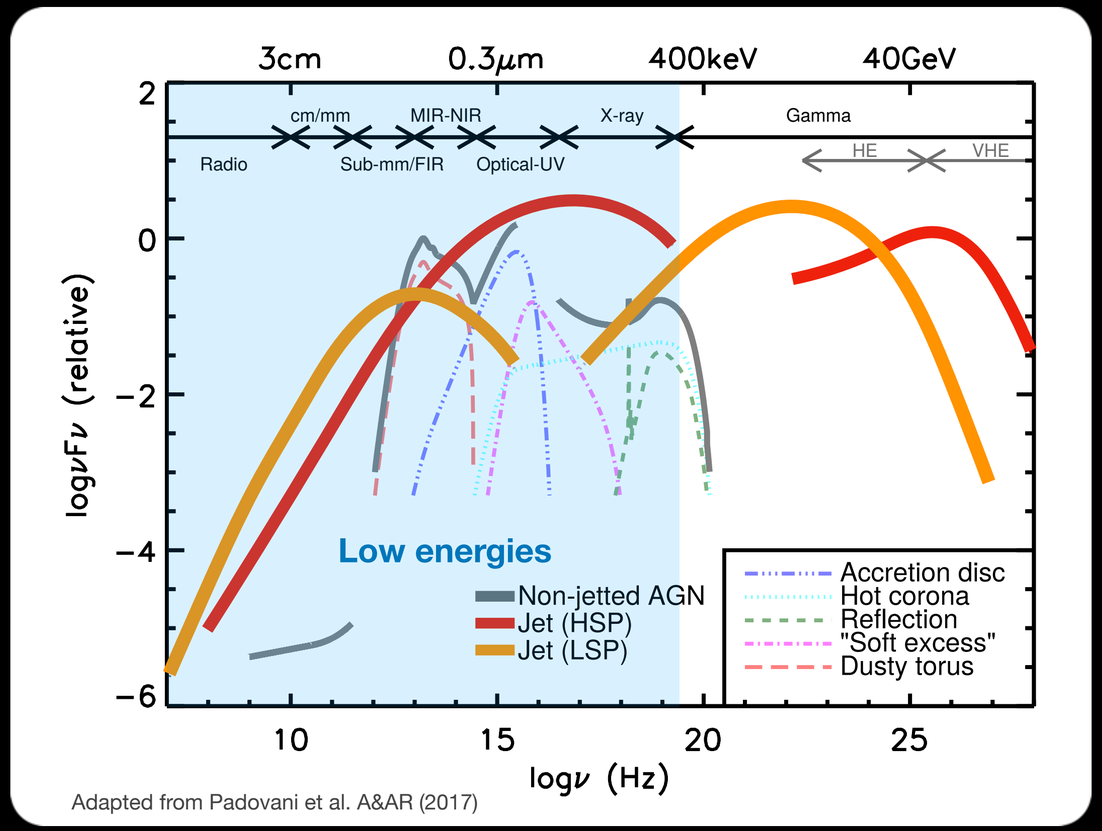

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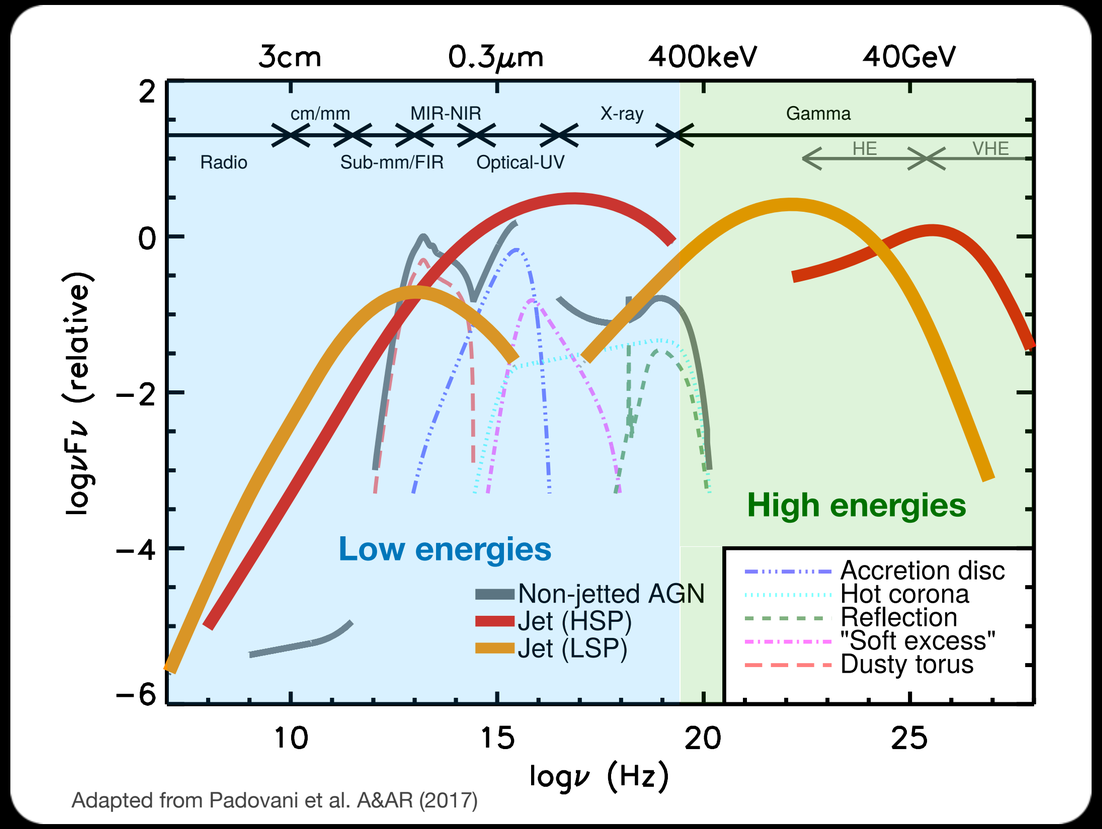

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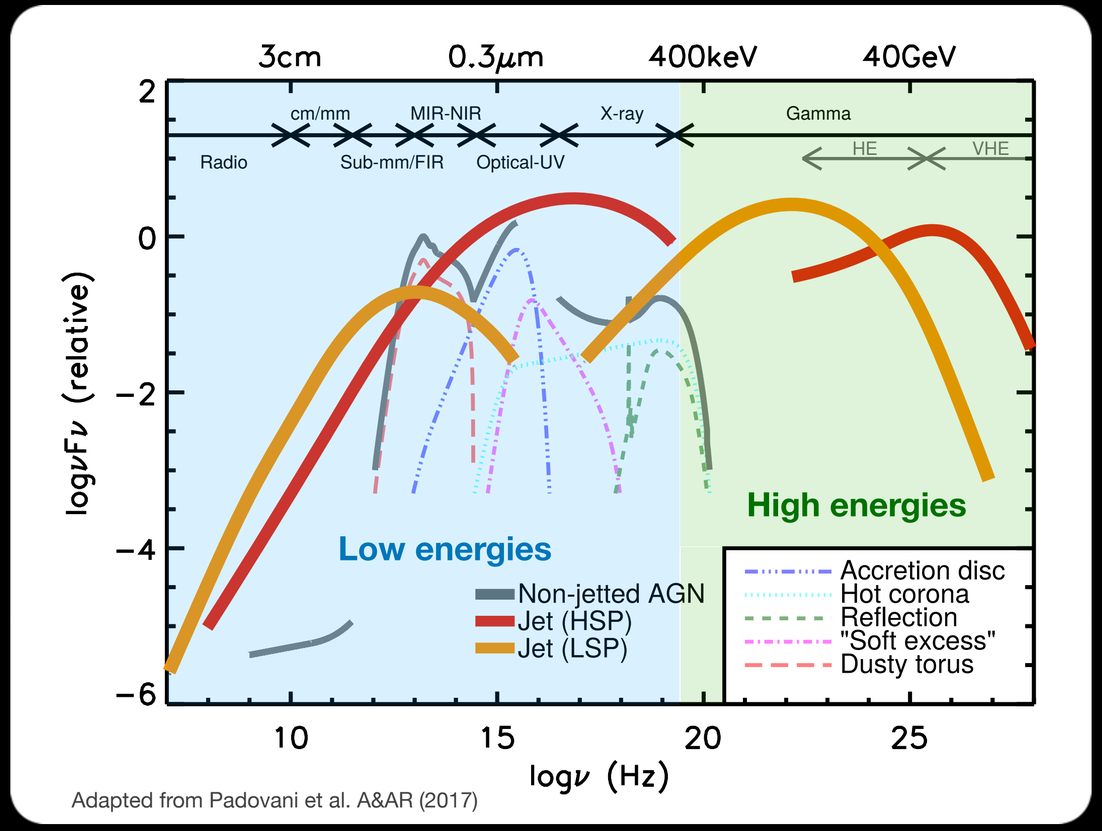

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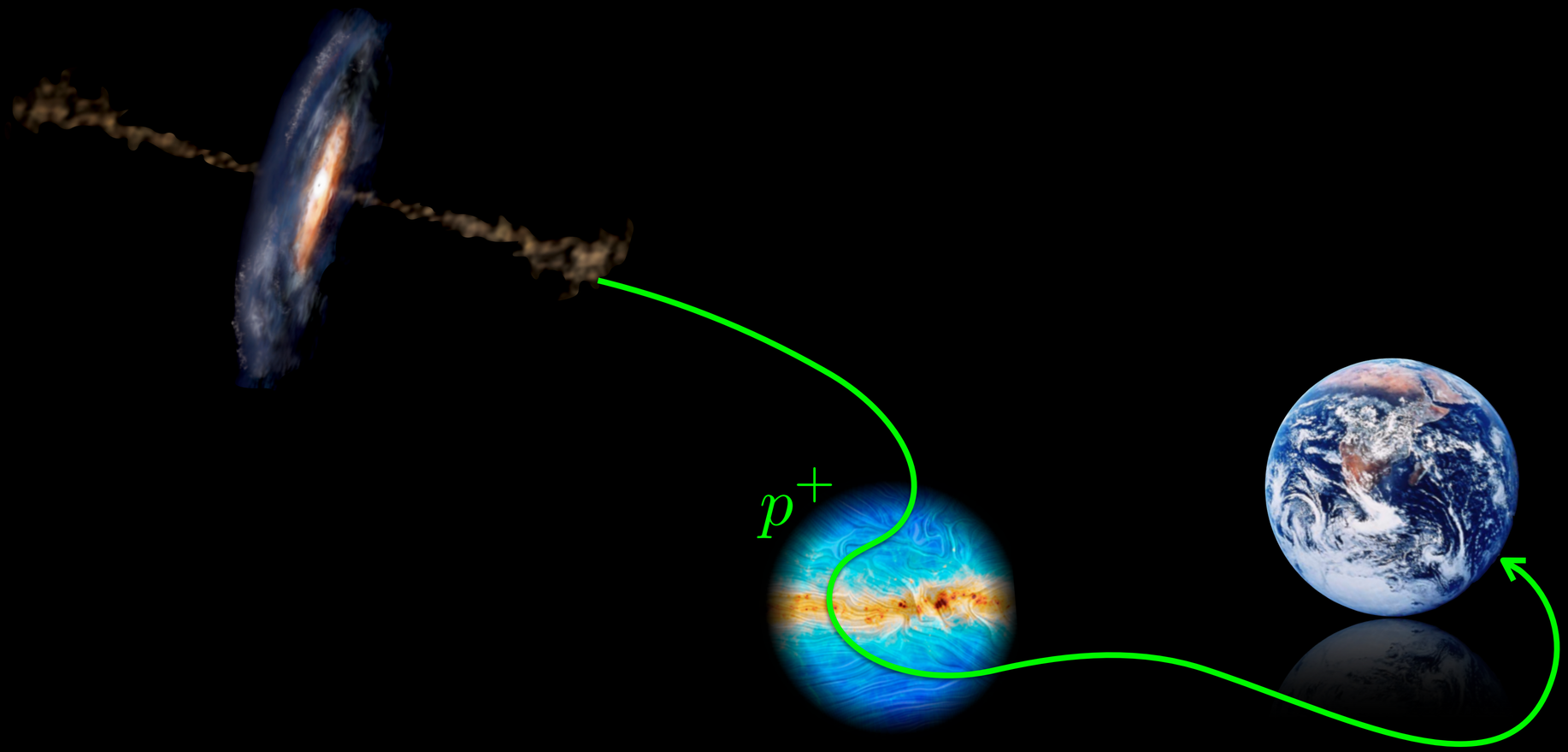
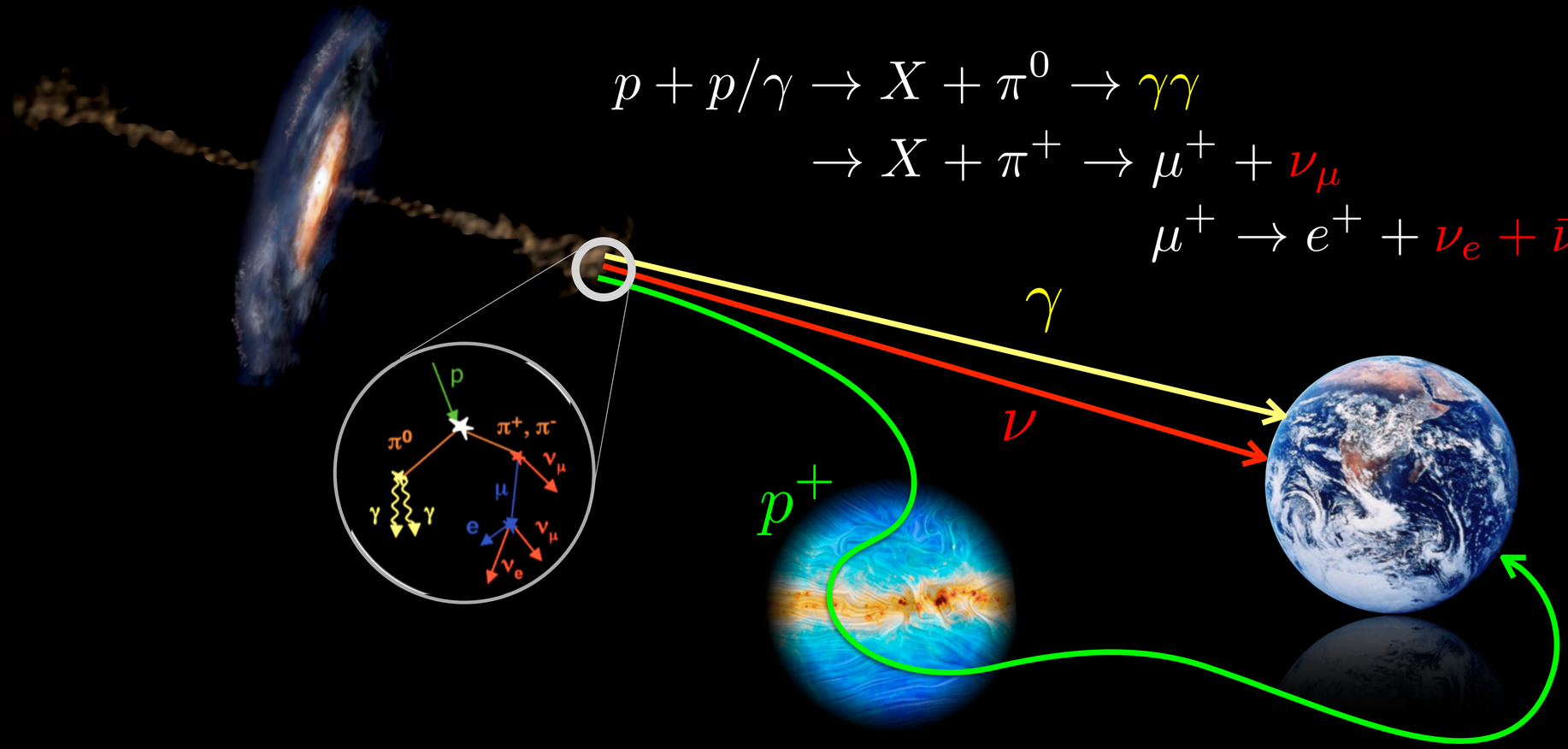
- **The identification of hadronic signatures would reveal AGN as cosmic ray accelerators, solving a long-standing question of UHECR origin.**
- It would also provide insights into the particle acceleration in extreme EM and gravitational environments.

HADRONIC PROCESSES IN AGN



HADRONIC PROCESSES IN AGN

$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ **(oscillates to ~1:1:1)**



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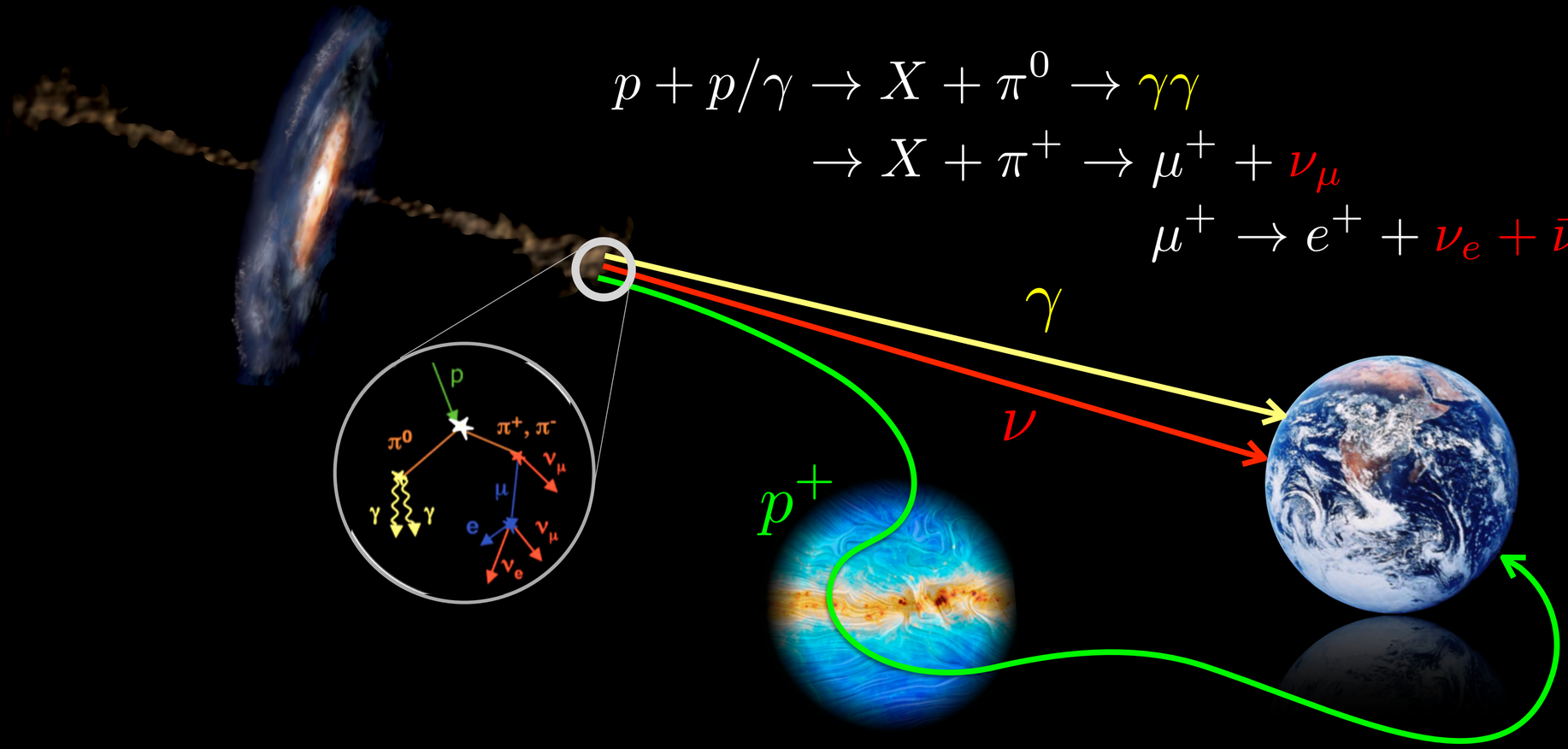

Gamma-ray flux **Neutrino flux**

$$\frac{K_\pi}{4} E_\gamma^2 F_\gamma(E_\gamma) \approx \frac{1}{3} \sum_{E_\gamma = 2E_\nu} E_\nu^2 F_\nu(E_\nu)$$

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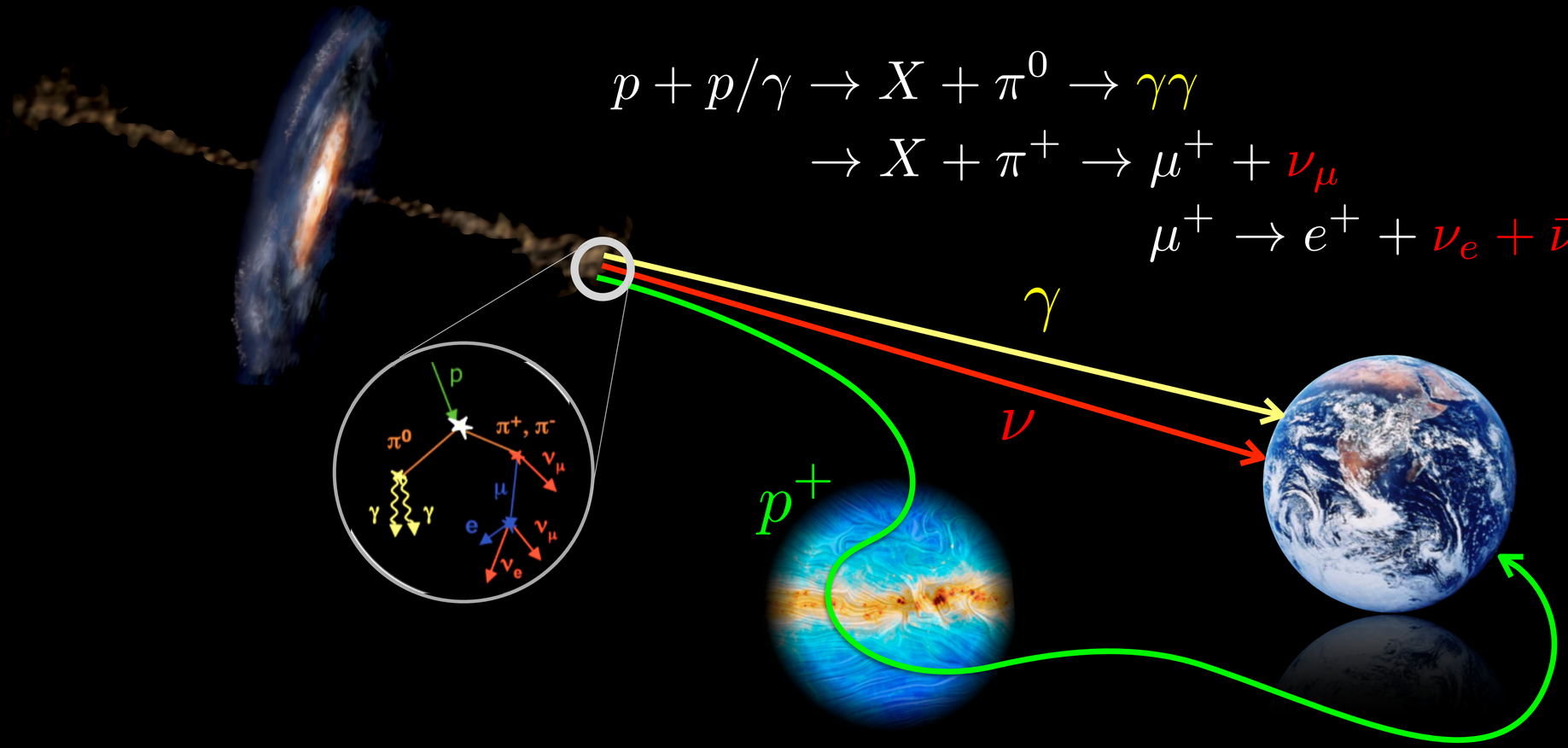

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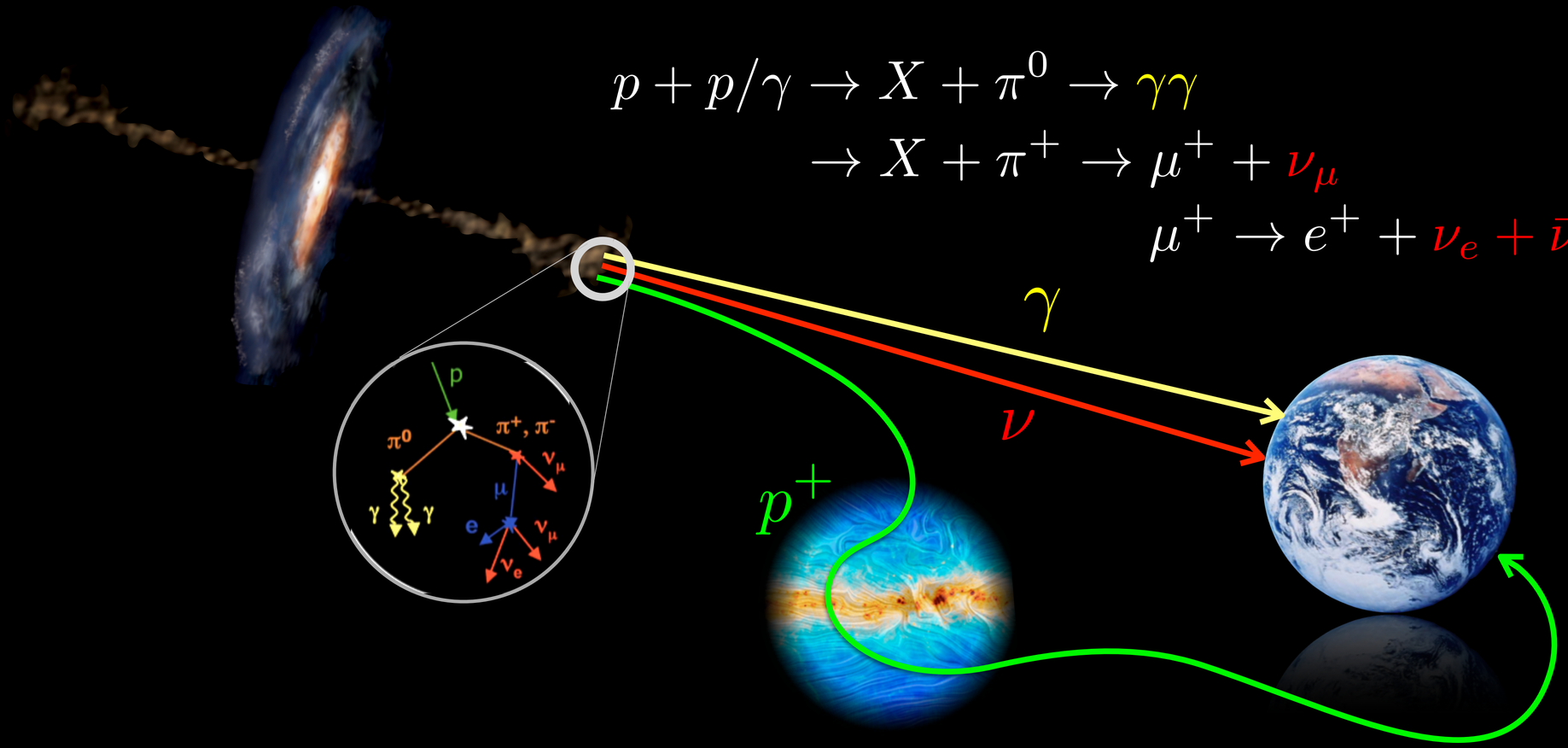

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  - Degeneracy between leptonic/hadronic/hybrid EM SED models.

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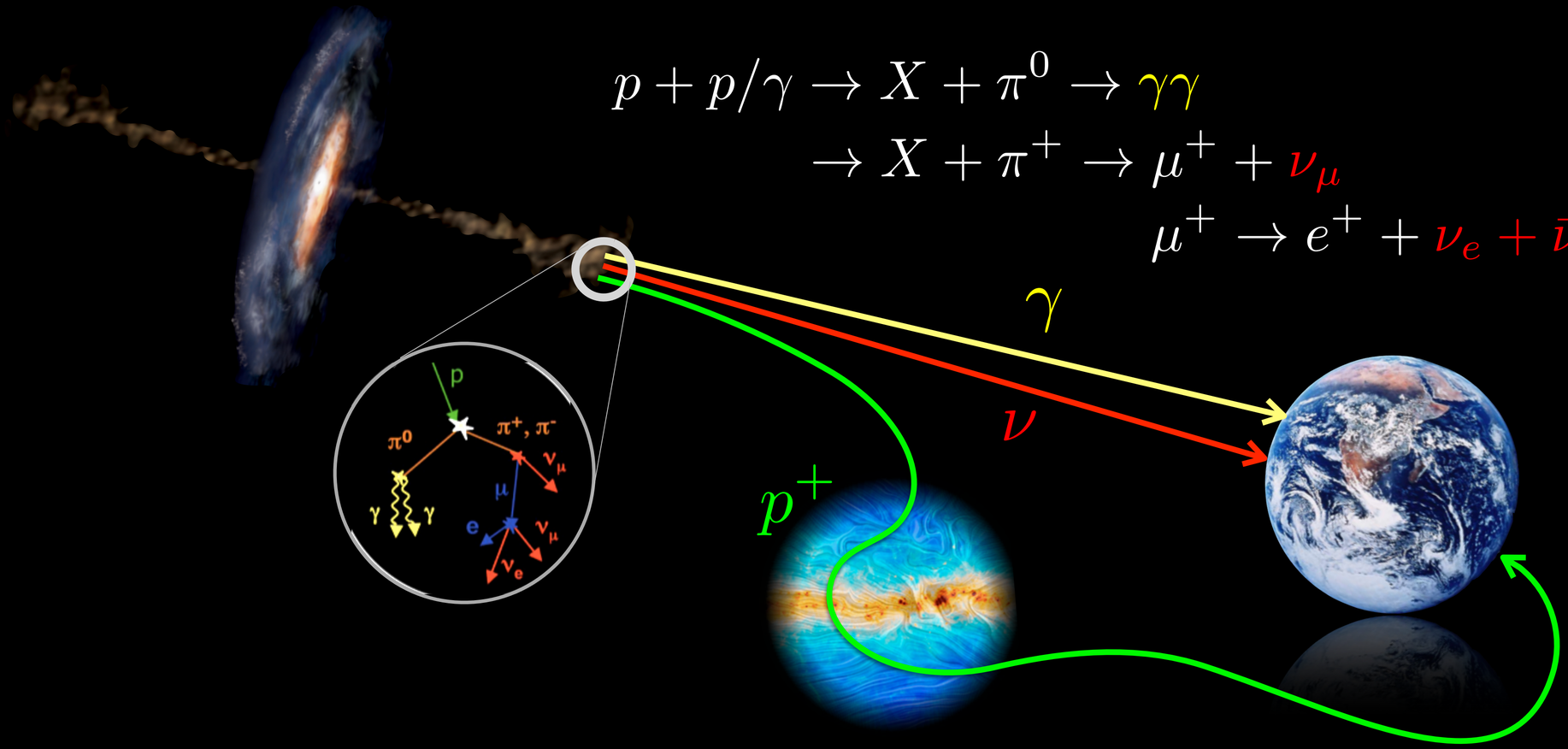

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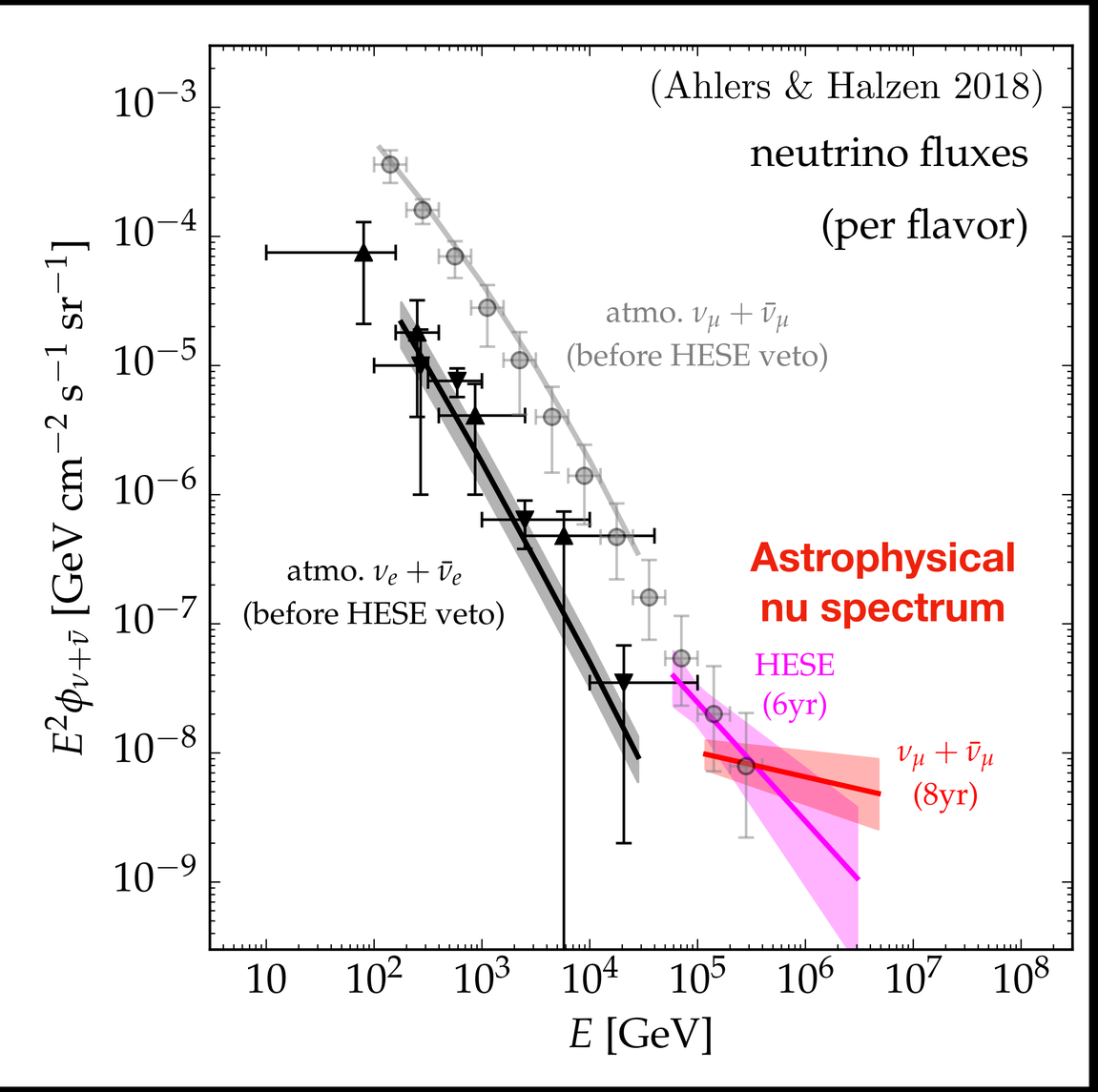
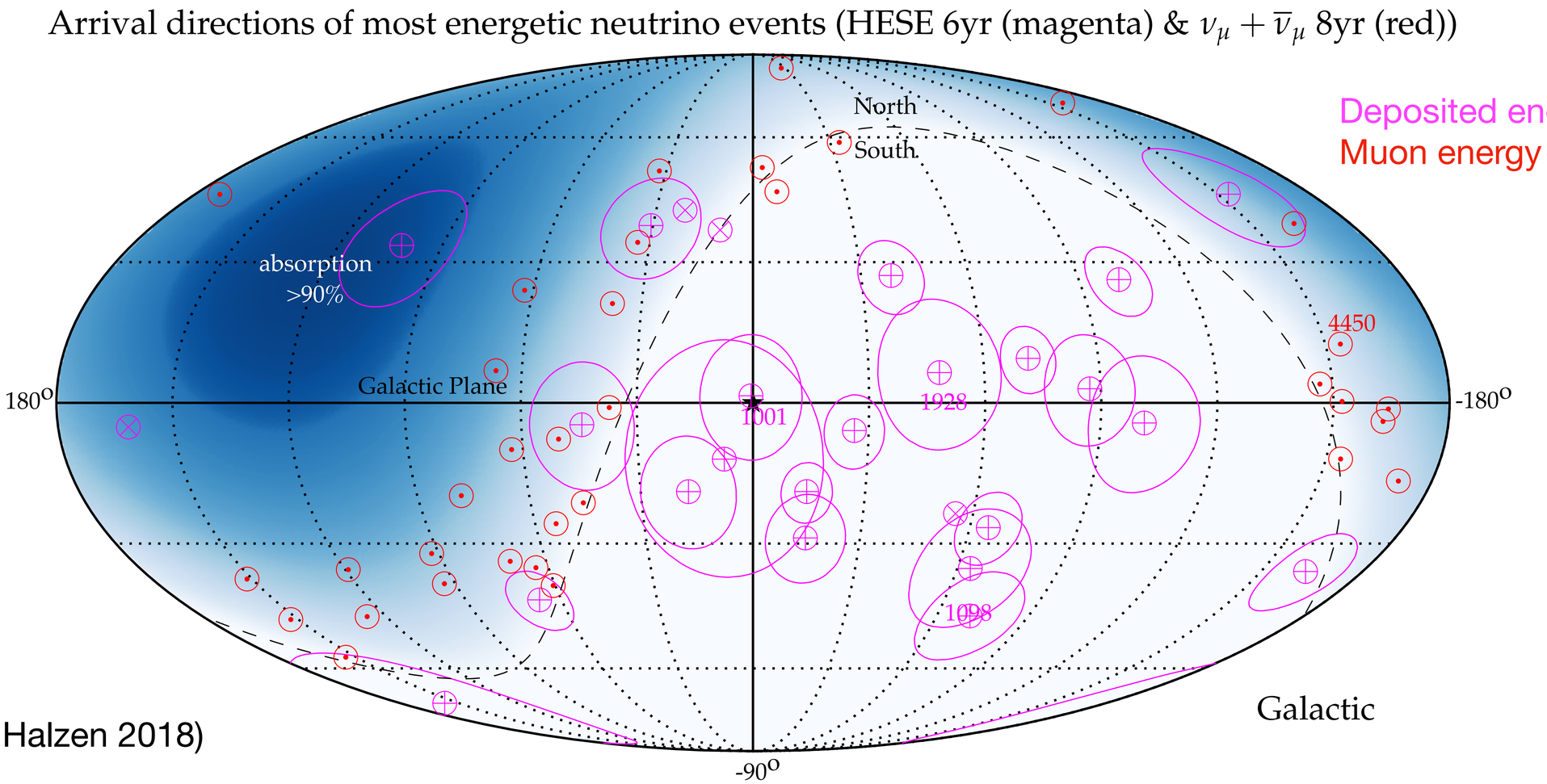
- **Challenges for hadronic EM identification:**
  - Degeneracy between leptonic/hadronic/hybrid EM SED models.
  - **Neutrinos are a smoking-gun signature of hadronic processes.**

HIGH-ENERGY ASTROPHYSICAL NEUTRINOS



- **Astrophysical neutrino flux detected by the IceCube neutrino observatory in the 10 TeV - 10 PeV energy range.**
- Atmospheric origin excluded at >8σ.
- Flux > 200 TeV consistent with a power-law spectrum with index ~ 2.2-2.8.
- Astrophysical flux dominates above ~200 TeV.

ASTROPHYSICAL NEUTRINOS - SKY DISTRIBUTION



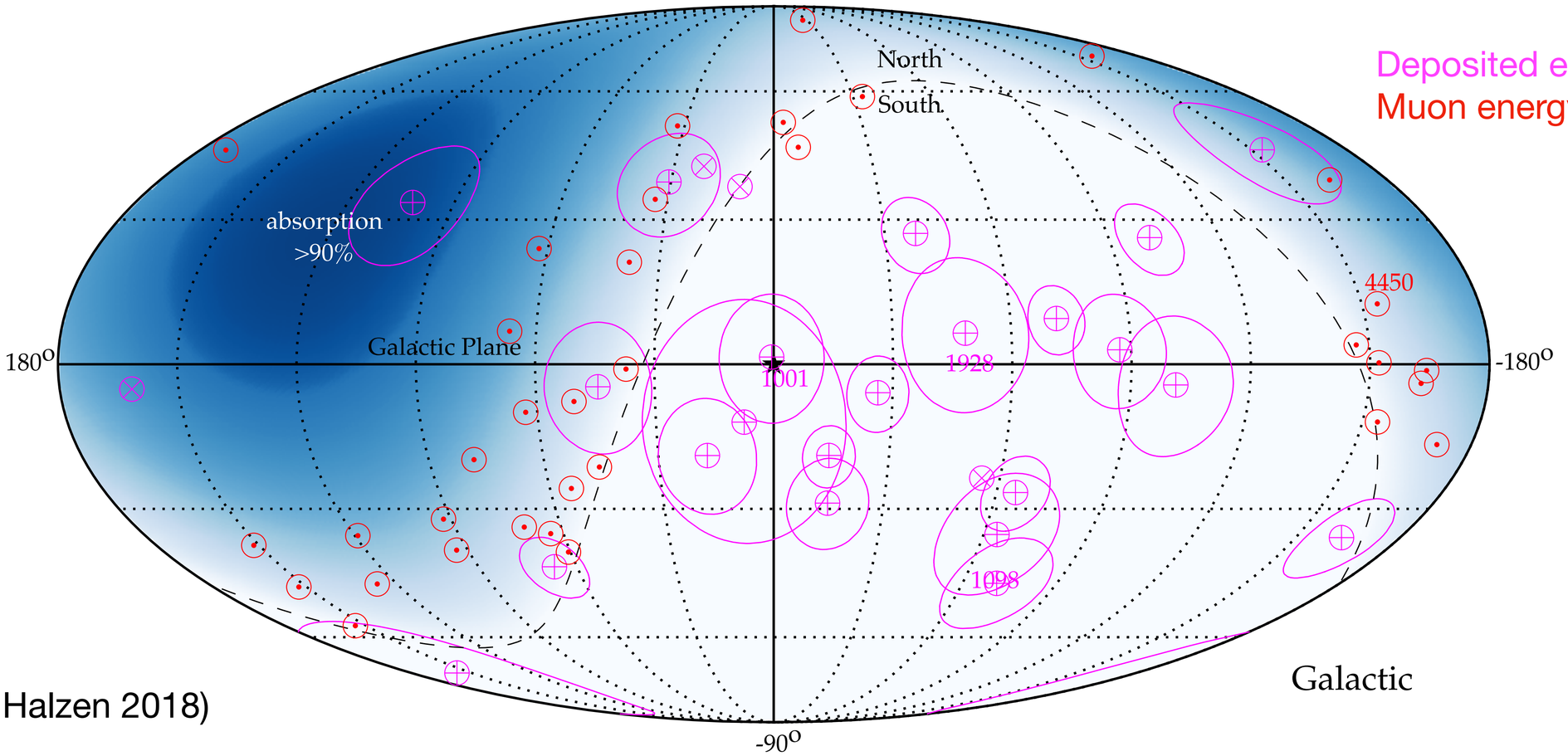
Deposited energy > 100 TeV
Muon energy > 200 TeV

(Ahlers & Halzen 2018)

- Consistent with isotropic distribution, favors **extragalactic origin**.
- No apparent correlation with Galactic plane.

ASTROPHYSICAL NEUTRINOS - SKY DISTRIBUTION

Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



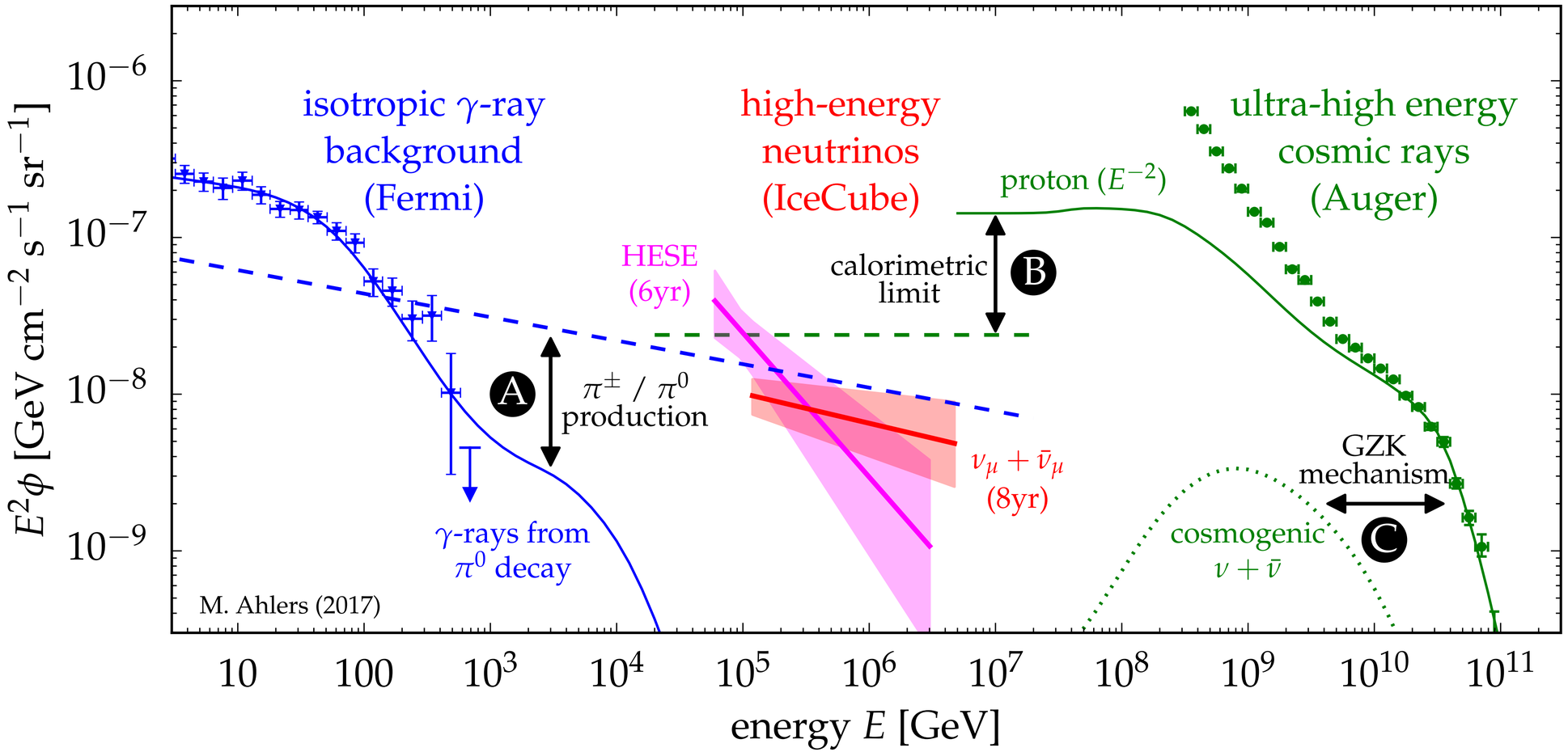
Deposited energy > 100 TeV
Muon energy > 200 TeV

(Ahlers & Halzen 2018)

- Consistent with isotropic distribution, favors **extragalactic origin**.
- No apparent correlation with Galactic plane.
- **HE event rate is low. ~O(10) events / year.**

MULTIMESSENGER CONTEXT

Ahlers & Halzen (arXiv/1805.11112)



- The higher energy end of the Fermi IGRB is dominated by unresolved BL Lacs (e.g. Di Mauro et al. arXiv/1311.5708)
- Implications regarding the gamma-ray opacity of the sources.

QUESTIONS FOR MULTIMESSENGER STUDIES OF AGN

- **What is the timescale of the multimessenger emission?** Steady flux vs flares. Acceleration and interaction timescales for cosmic rays.

- **Where are neutrinos and hadronic gammas produced?** Opacity of the source to gamma rays, cascading.

- **In what energy range is the hadronic emission more prominent?** Are all VHE gamma rays absorbed? Is the X-ray to MeV range the best range for follow-up studies.

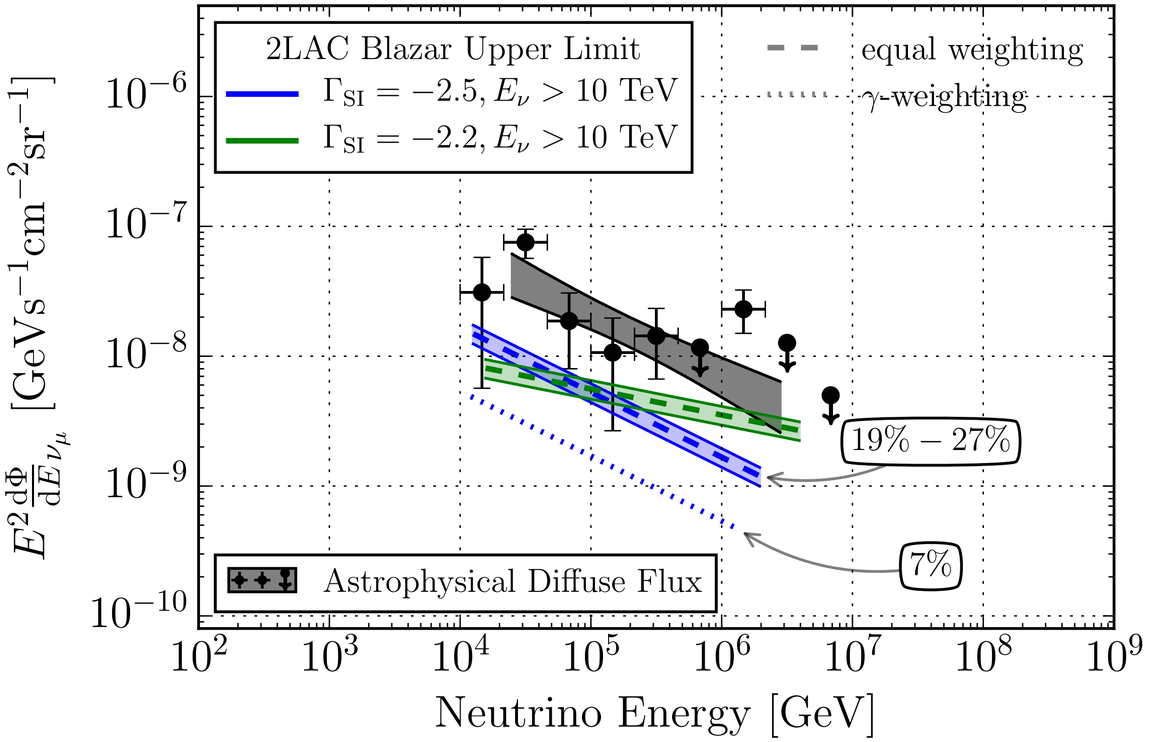
- **Is there a prototypical neutrino AGN class or several?** Spectral features, etc.

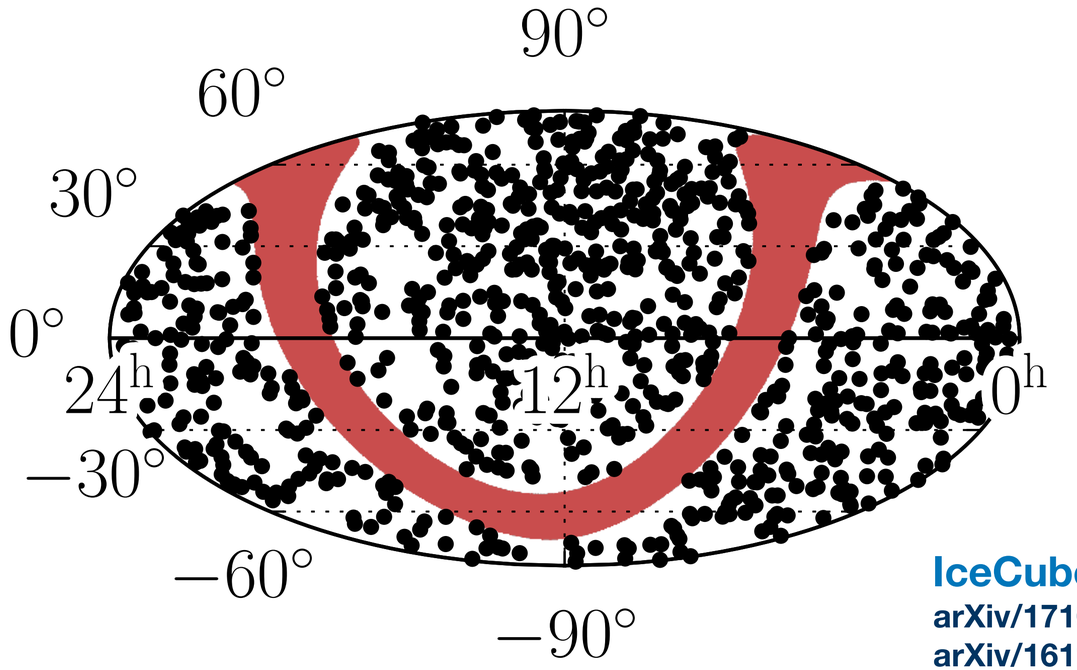
CONNECTING THE NEUTRINO ASTROPHYSICAL FLUX WITH AGN

- **Time/spatial autocorrelations**
  - Clustering of neutrino events in time and space.

- **Correlations with multimessenger signals**
  - Association of neutrino clusters or high-energy neutrino events with known AGN (quiescent or flaring).
  - Association between single high-energy neutrinos of potential astrophysical origin and EM sources. Potential for singling out processes within those sources.

NEUTRINOS FROM GEV GAMMA-RAY BLAZARS





IceCube
arXiv/1710.01179
arXiv/1611.03874

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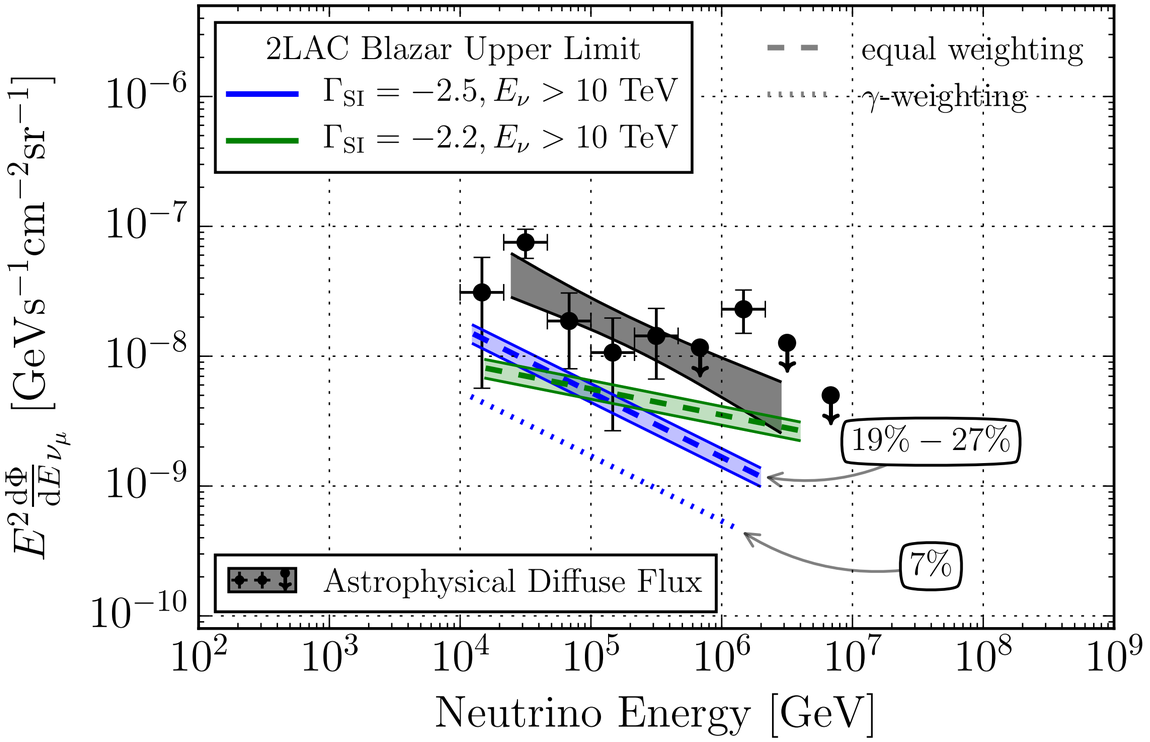

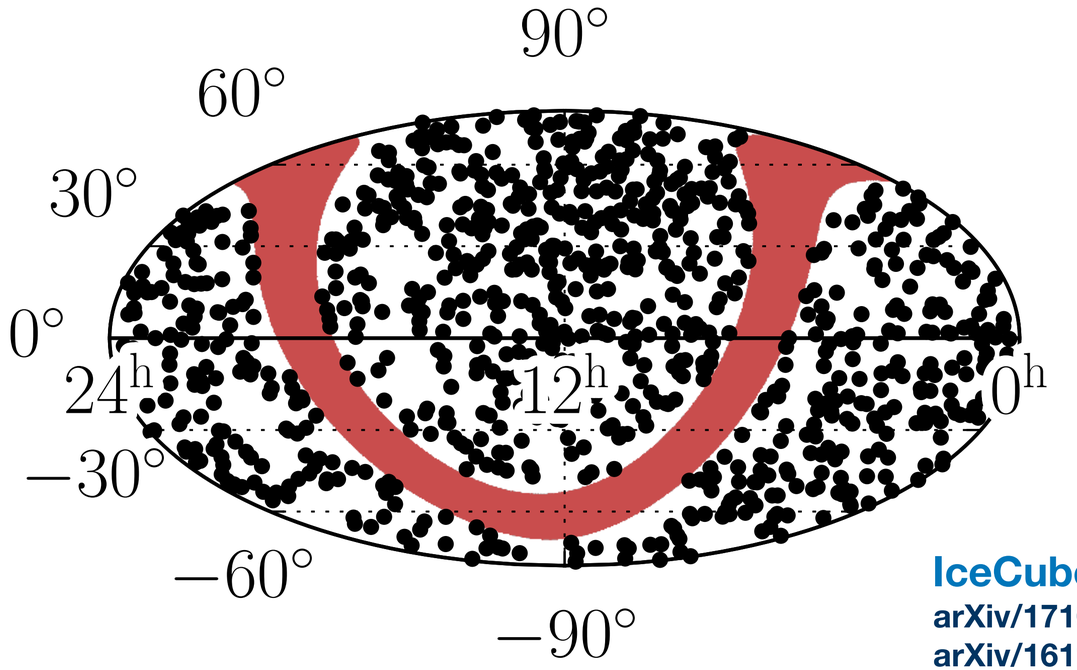

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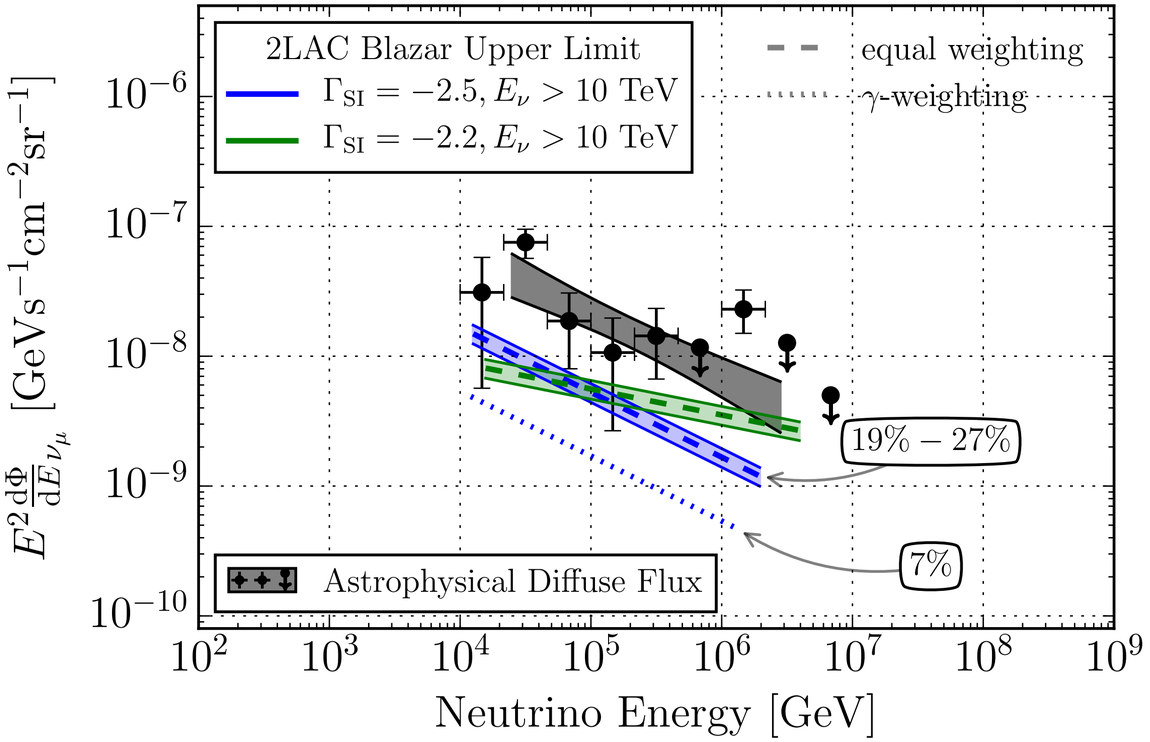

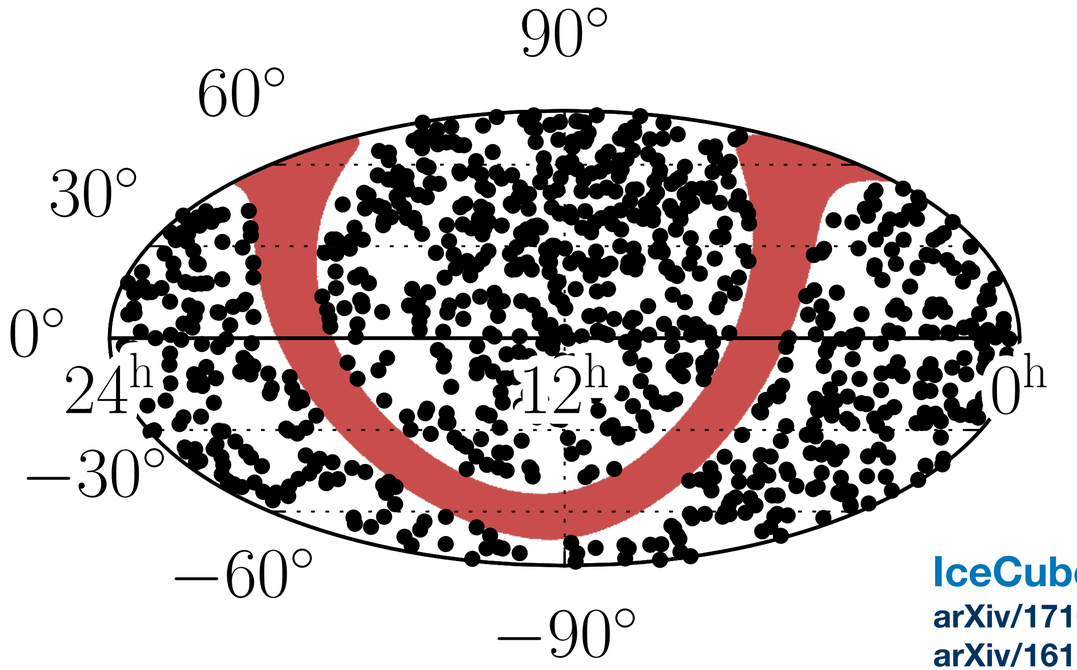

IceCube
arXiv/1710.01179
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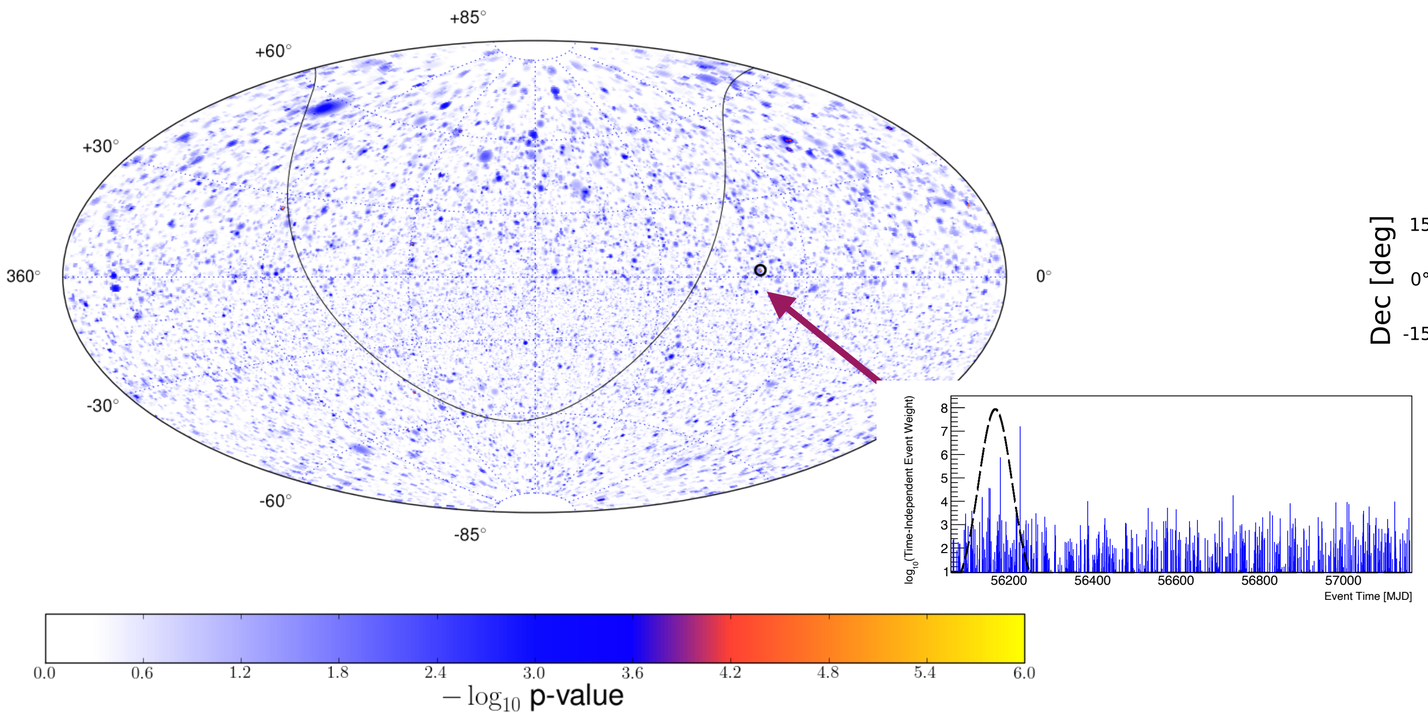
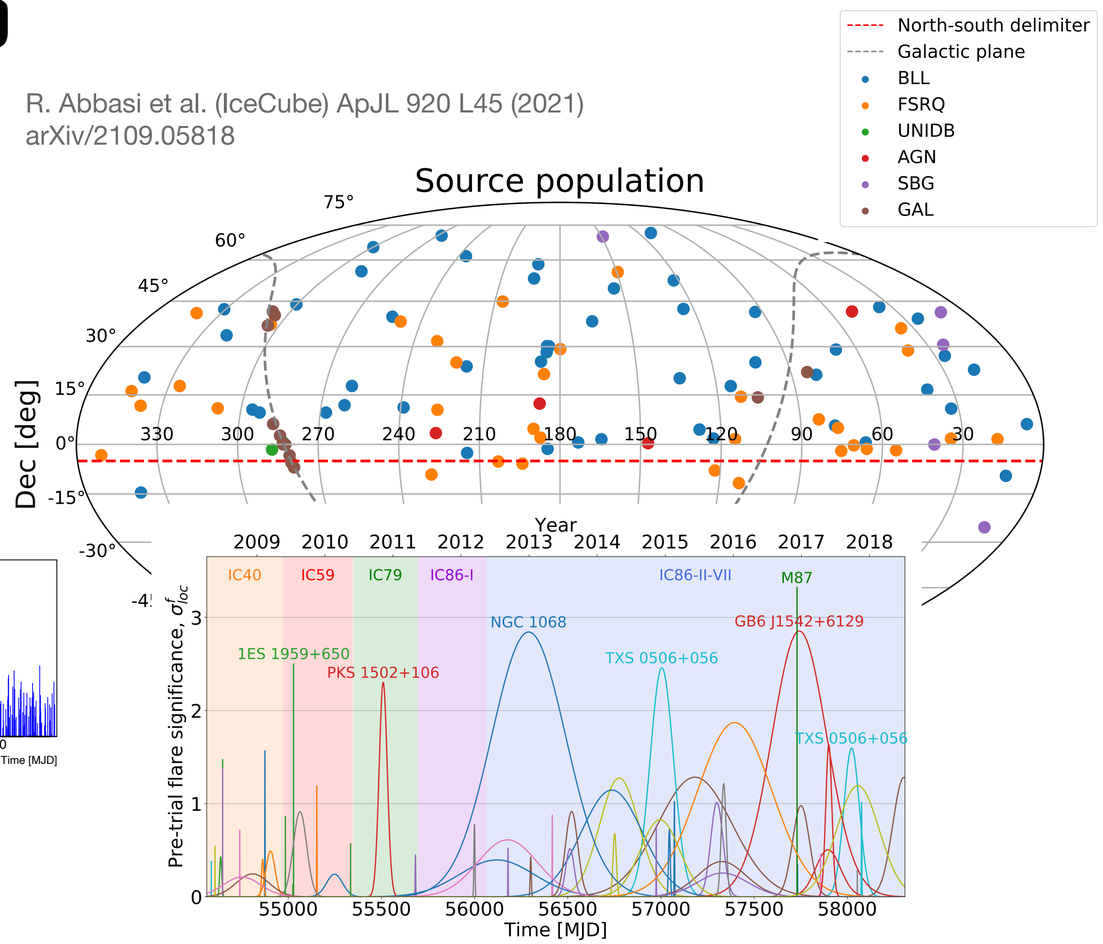
- Stacked search for neutrino emission from blazars in Fermi AGN catalogs.
- **No neutrino emission detected.** **Upper limits at the level of 6-27% of all-sky flux.**

TIME-DEPENDENT EMISSION SEARCHES

R. Abbasi et al. (IceCube) ApJ 911 (2021) 1, 67
arXiv/2012.01079



R. Abbasi et al. (IceCube) ApJL 920 L45 (2021)
arXiv/2109.05818

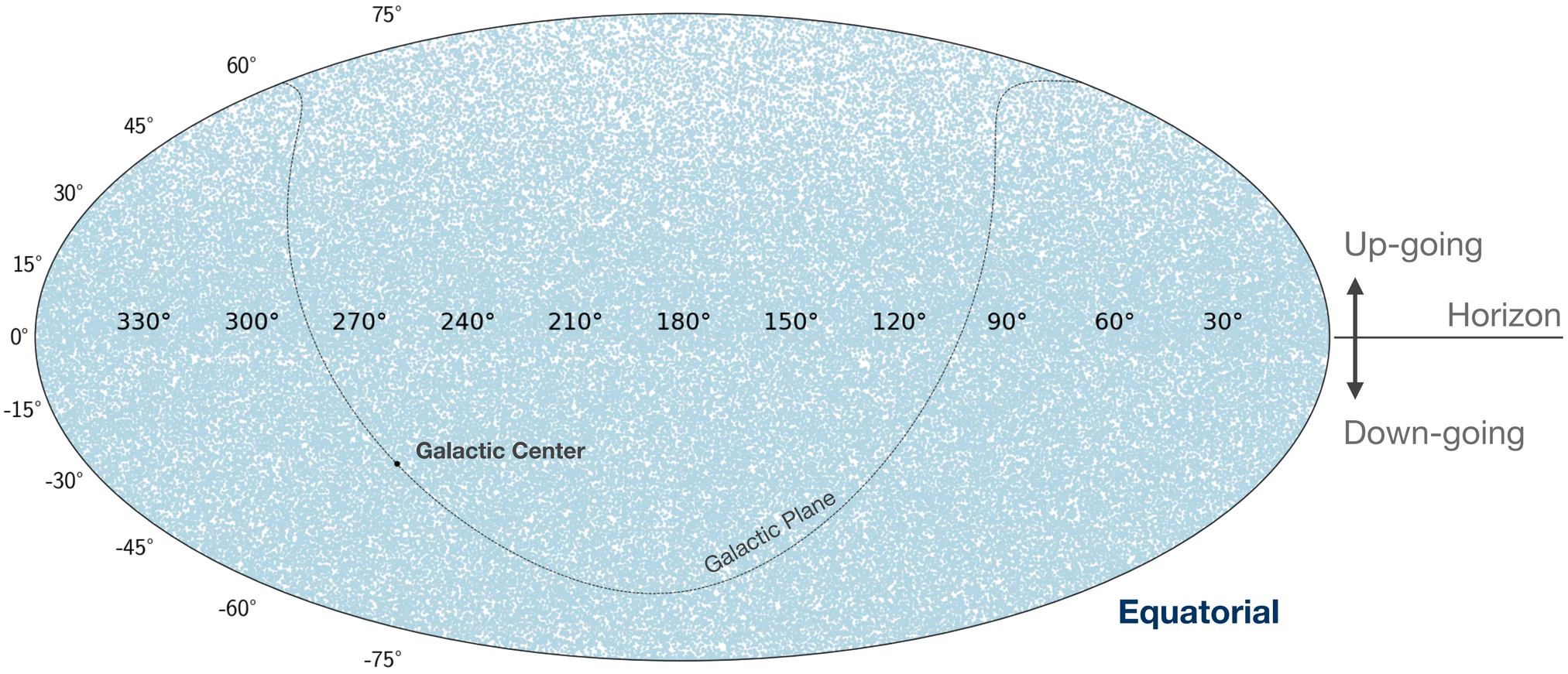


- **No significant temporal/spatial clustering (p-value 18%) in a five-year all-sky all-sky search (2012-2017).**
- No emission from the June 2015 flare of 3C 279.

- **Search for multiple "flares" from a catalog of sources (mostly AGN).**
- Population study shows a 3σ excess associated with four AGN.

ONE YEAR OF ICECUBE NEUTRINOS

https://icecube.wisc.edu/science/data/PS-IC86-2011



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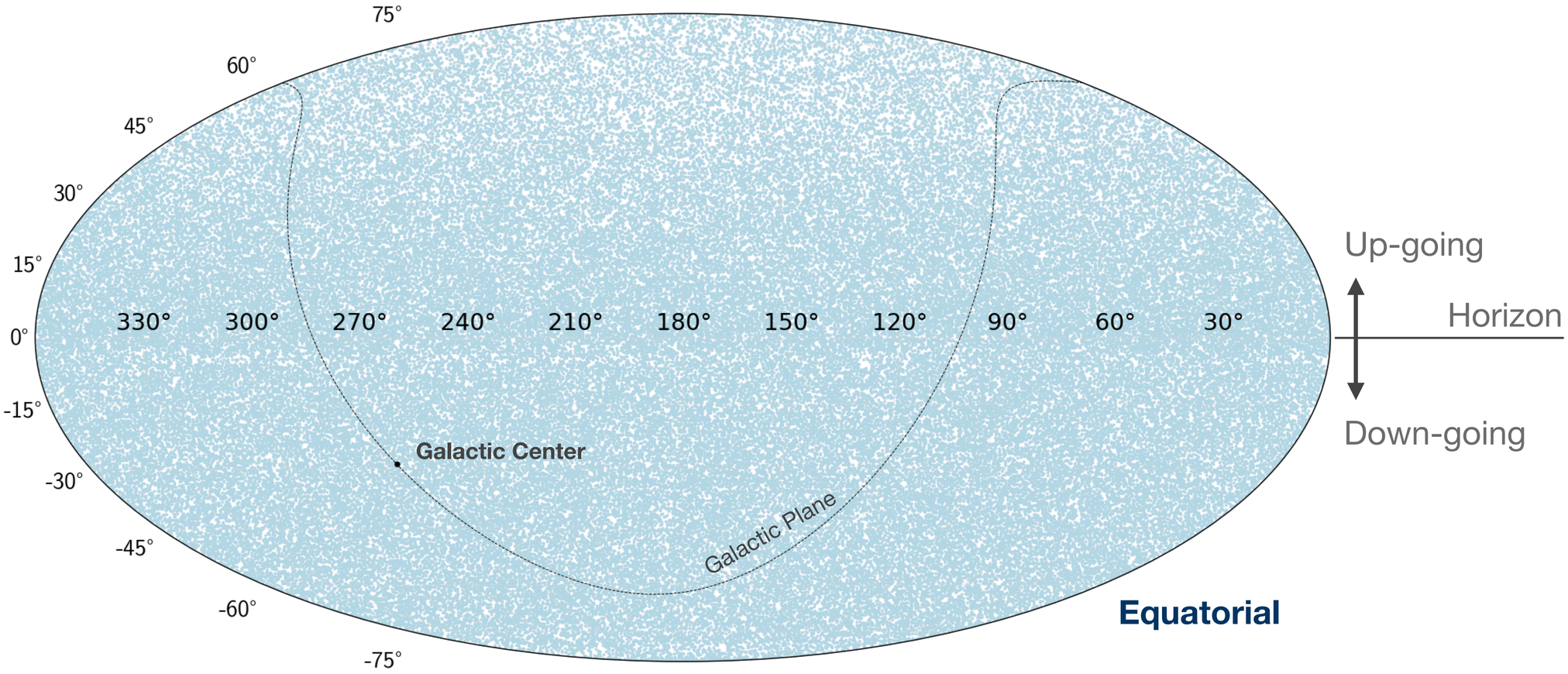

- 138,322 neutrino candidates from the first year of full IceCube operations.

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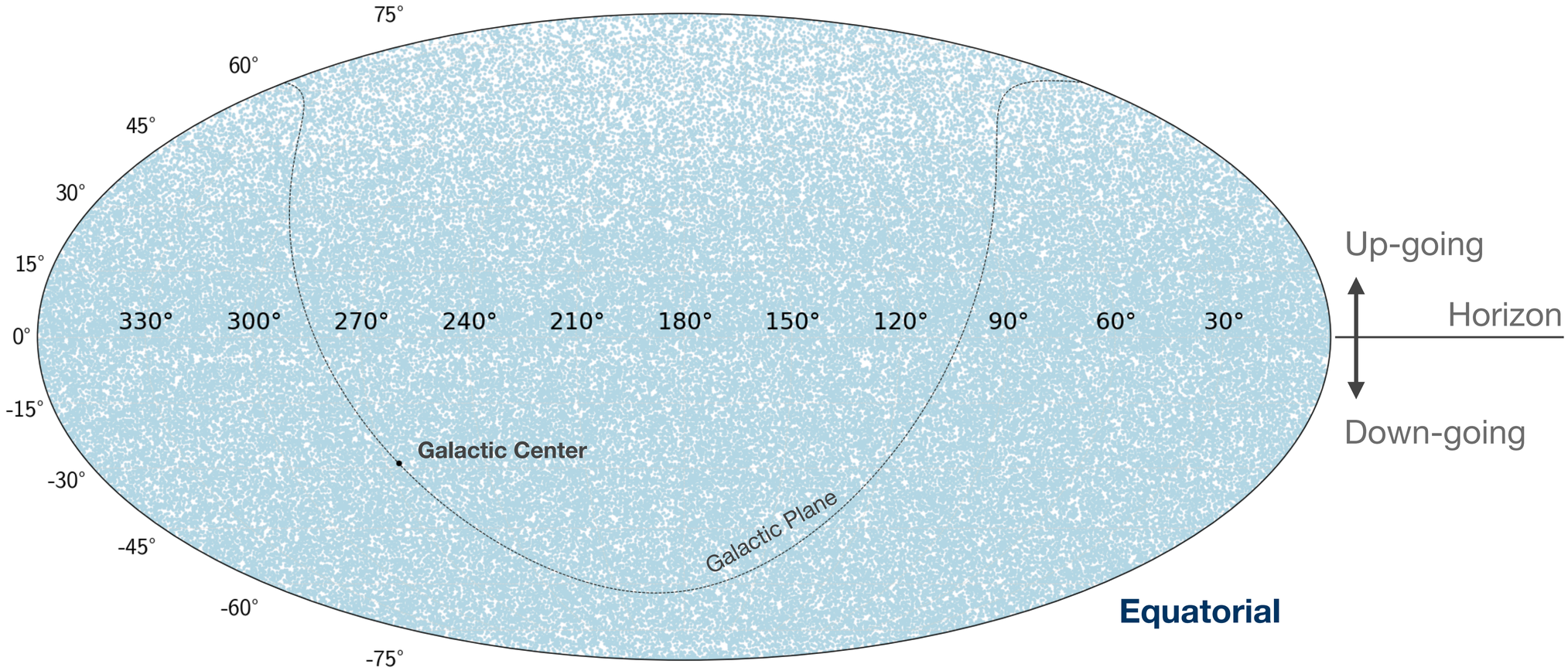

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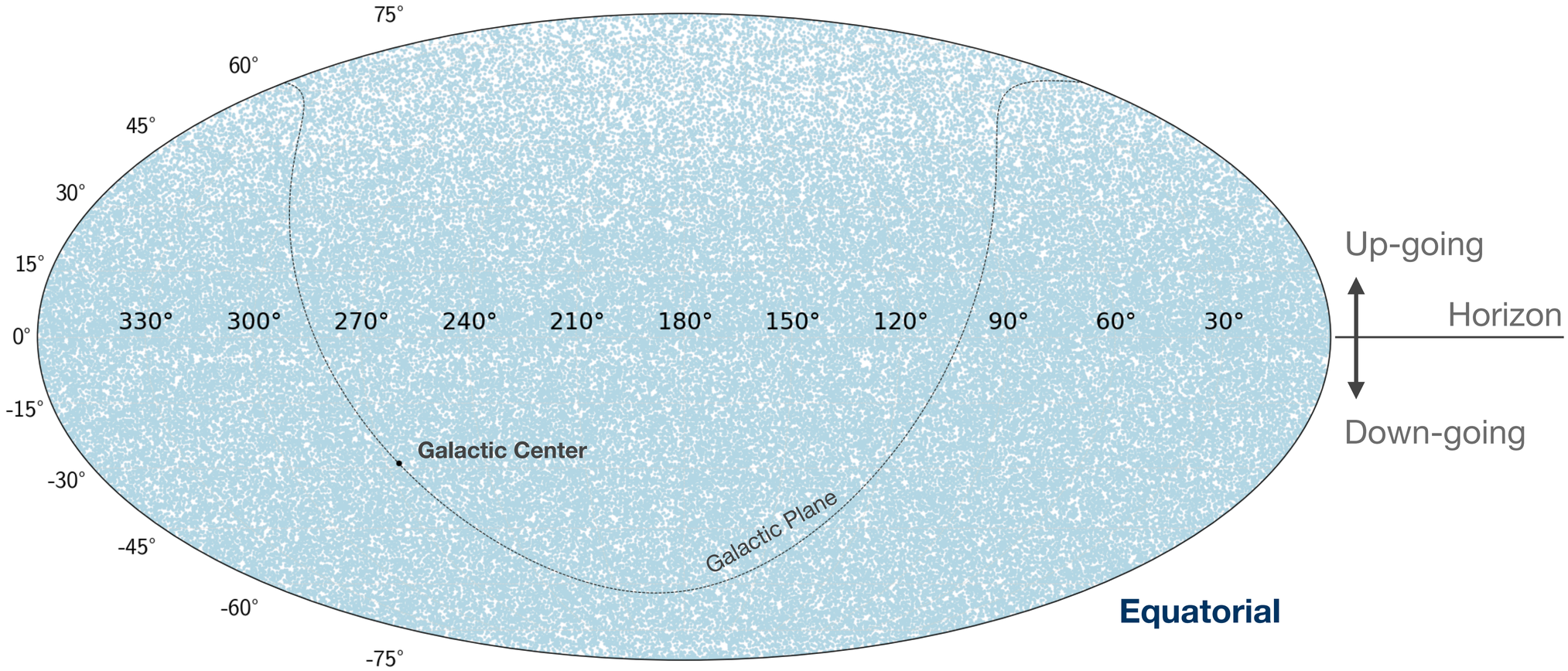

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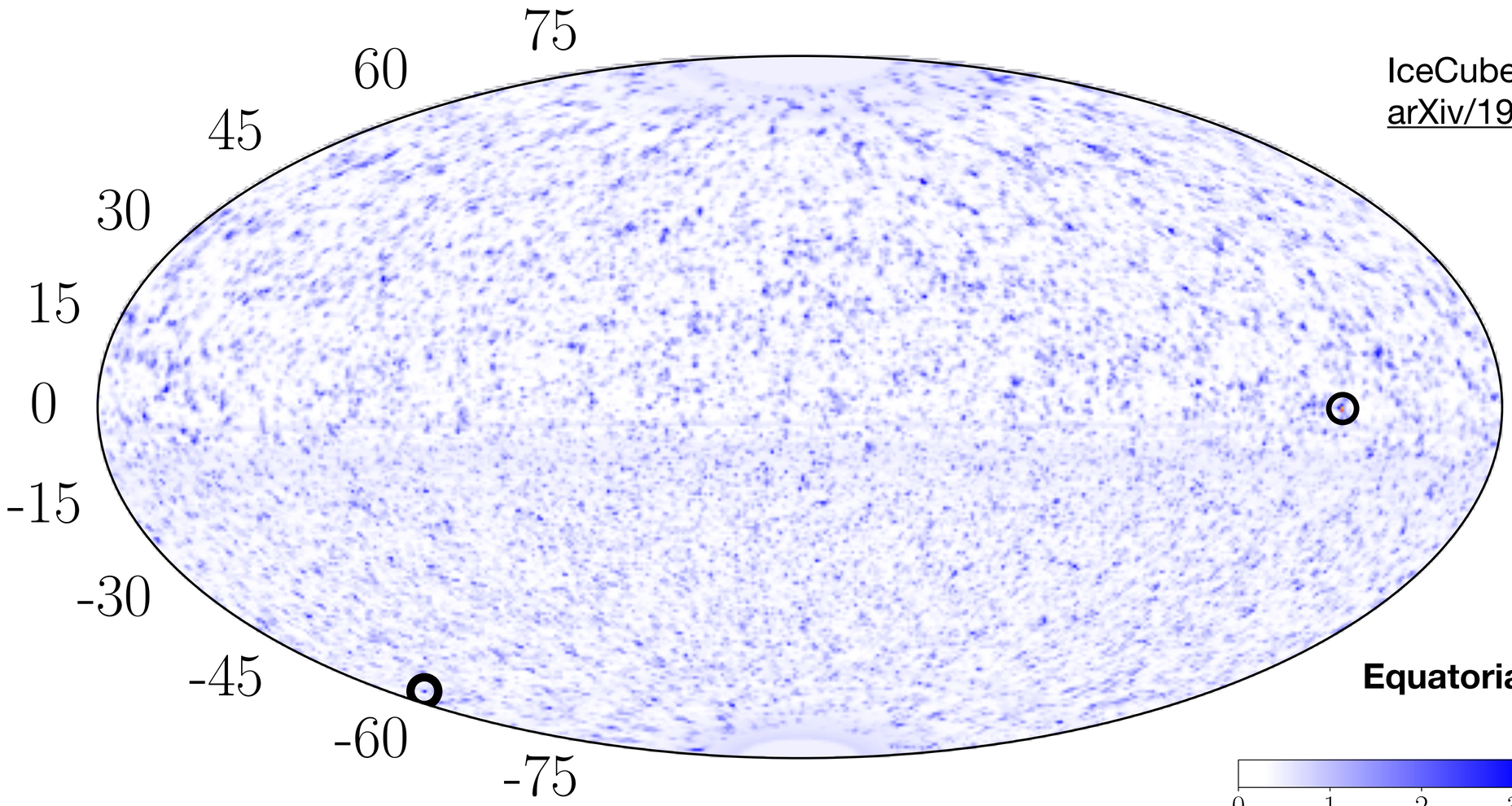
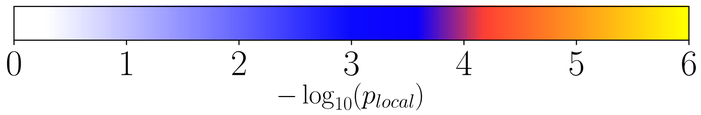
- **Search for neutrino self-clusterings that evidence a point source.**

SEARCH FOR POINT SOURCES IN 10 YEARS OF ICECUBE DATA



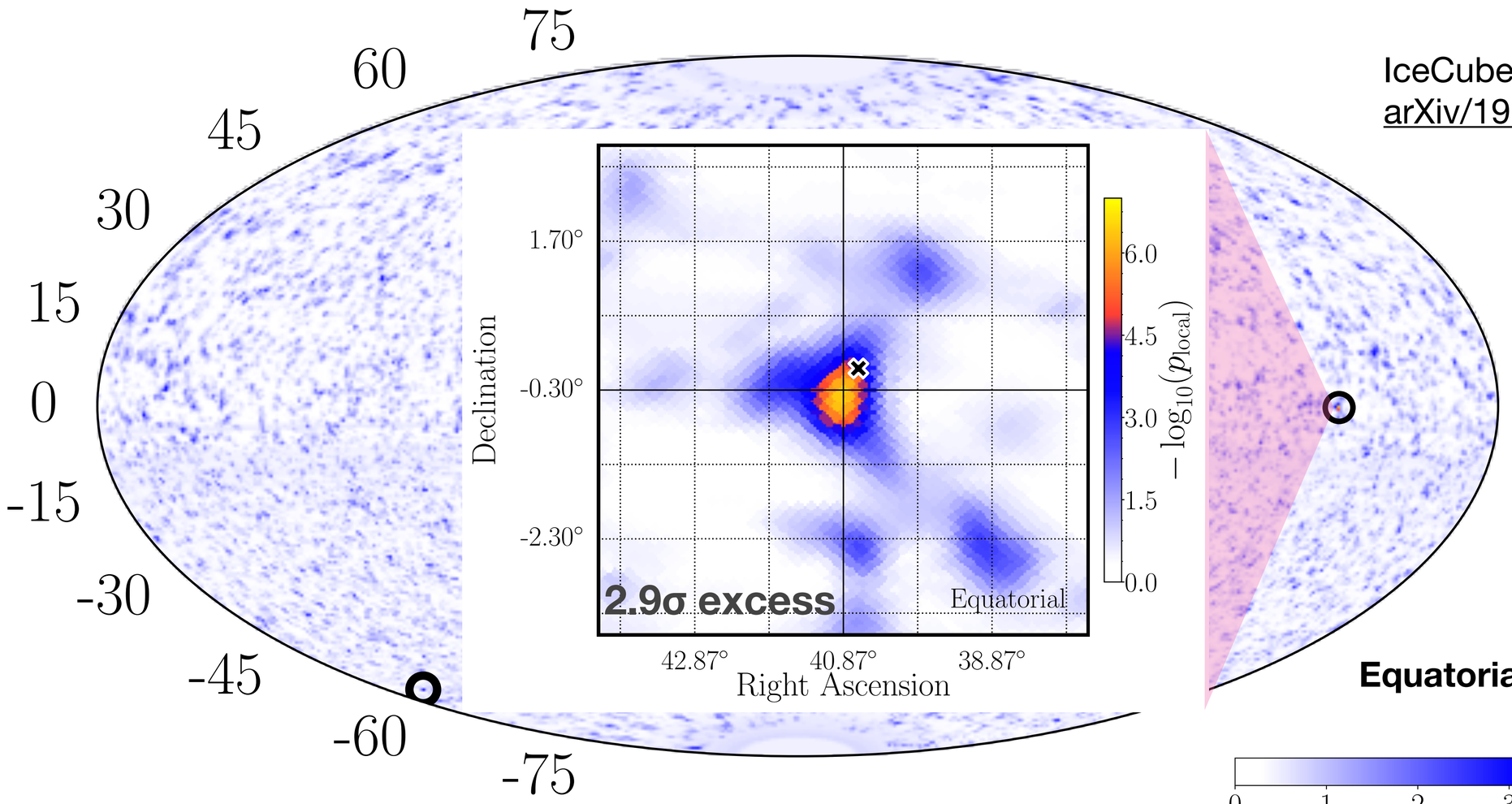
IceCube Collab. (2019)
arXiv/1910.08488

Equatorial

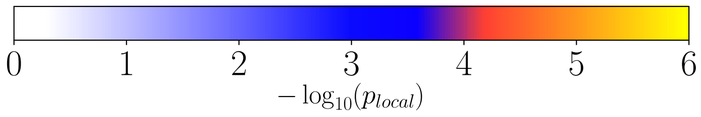


- Hottest spot in the North near Seyfert galaxy NGC 1068, **2.9σ** excess
- **3.3σ** from a source catalog search

SEARCH FOR POINT SOURCES IN 10 YEARS OF ICECUBE DATA



IceCube Collab. (2019)
arXiv/1910.08488



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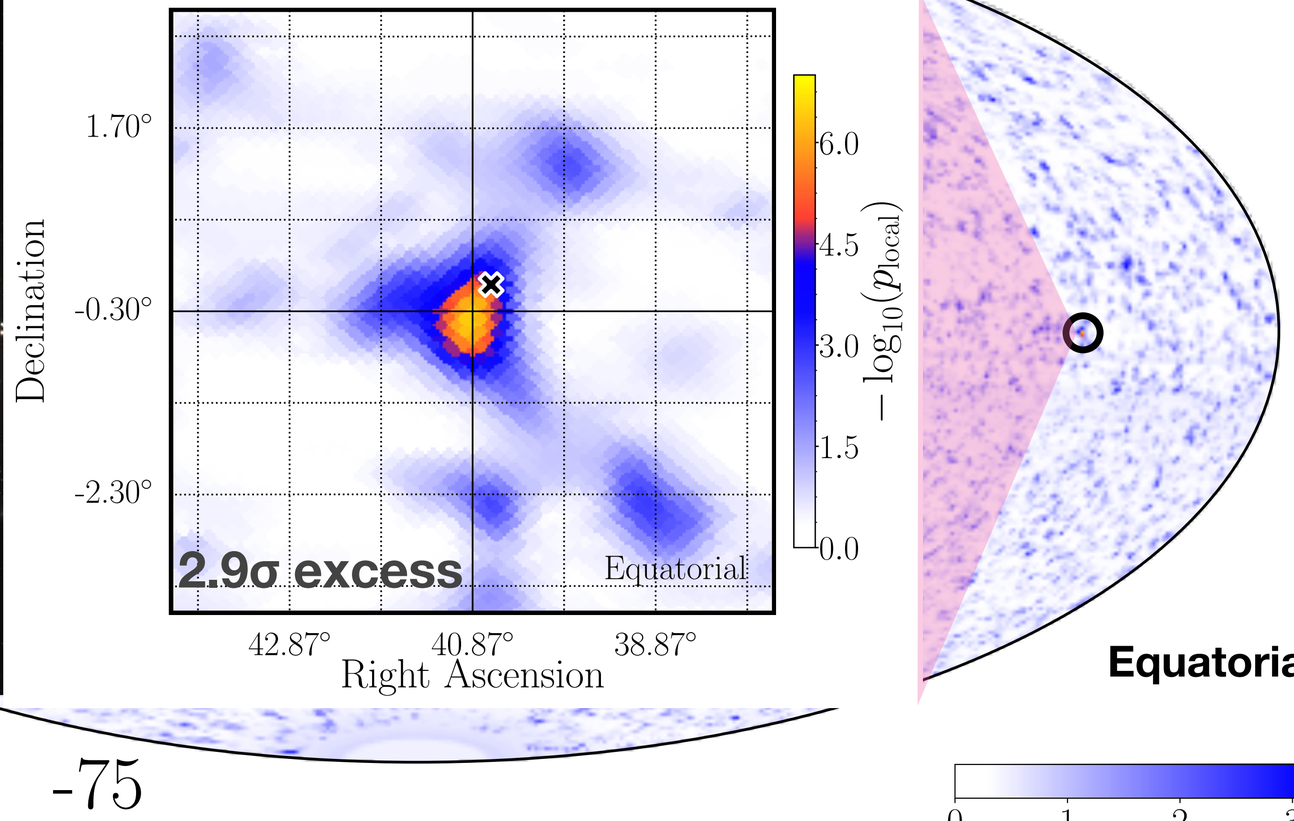

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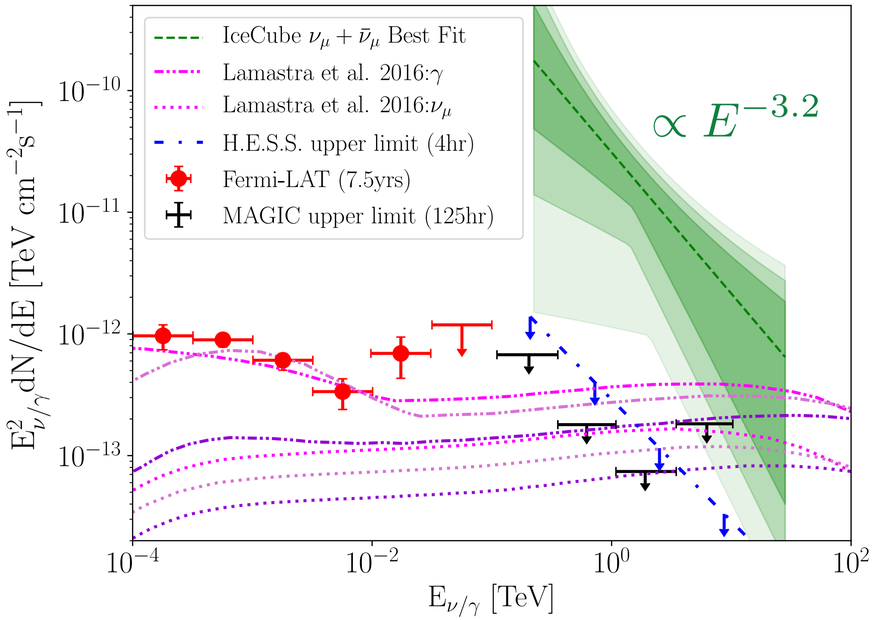
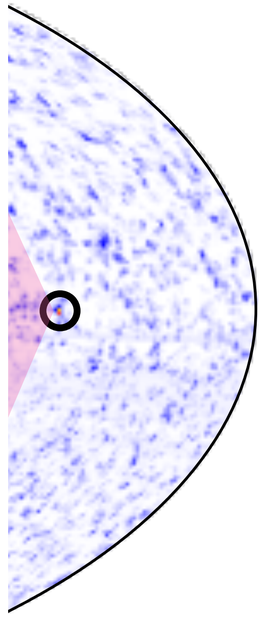
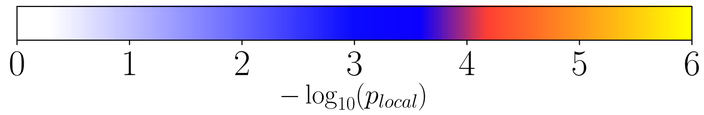




Equatorial



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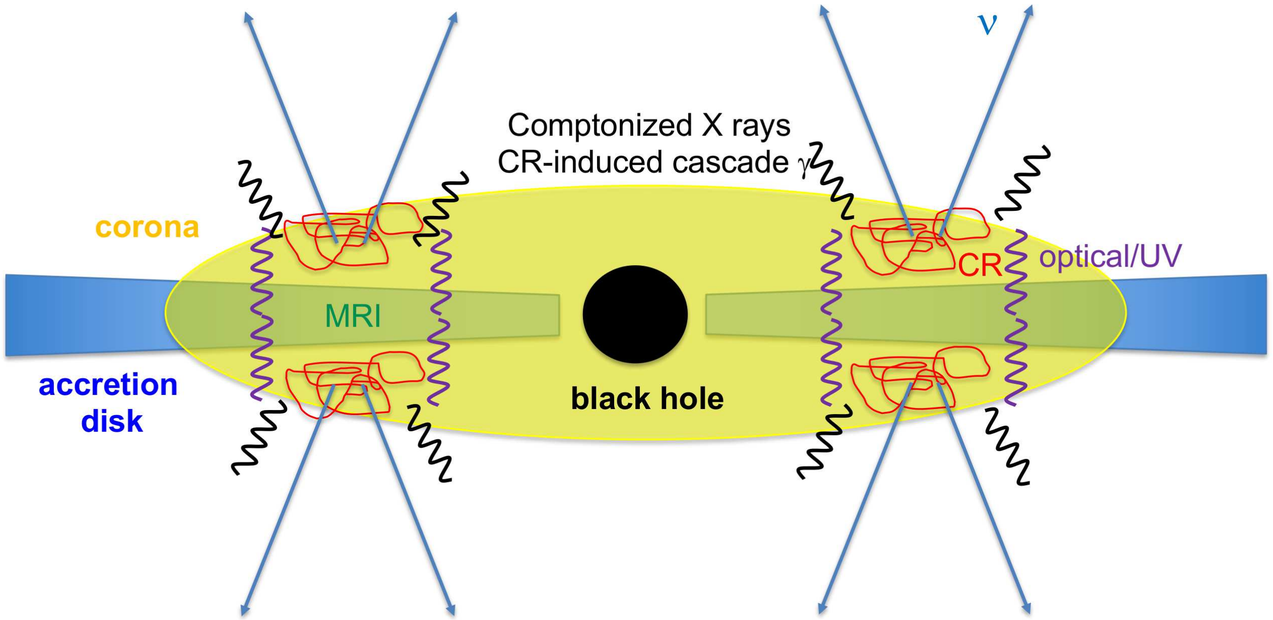
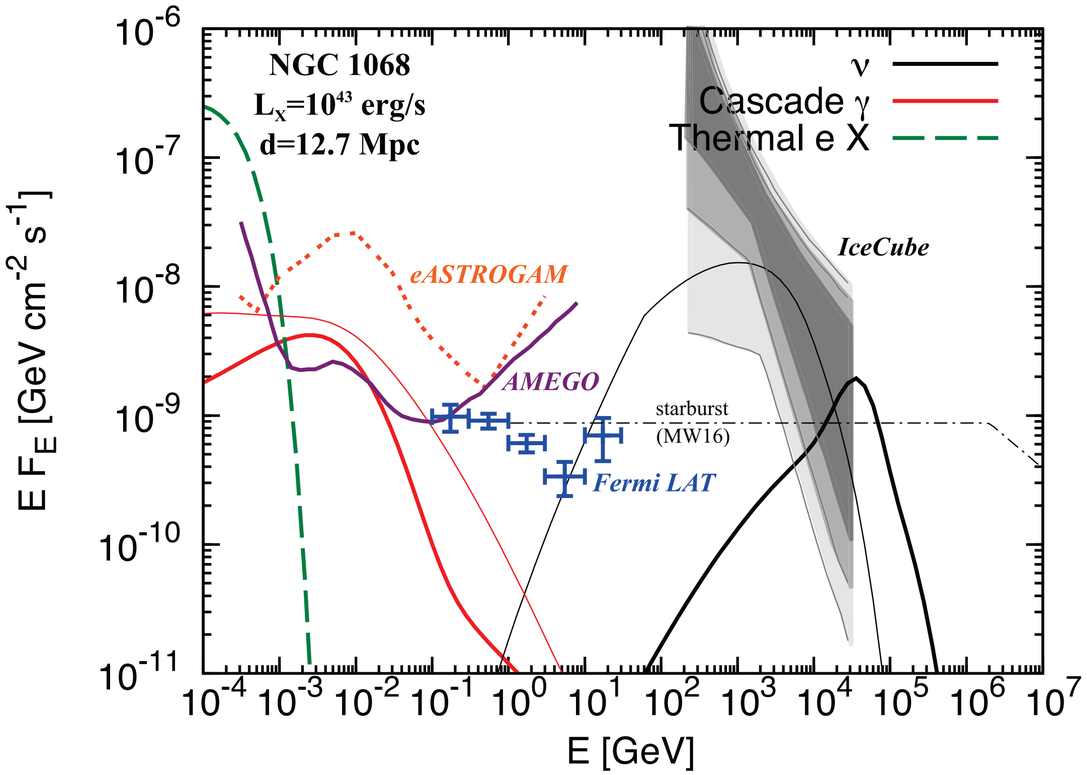
NEUTRINOS FROM HIDDEN AGN CORES?

K. Murase, S. Kimura, P. Meszaros, PRL 125 (2020) 011101
arXiv/1904.04226



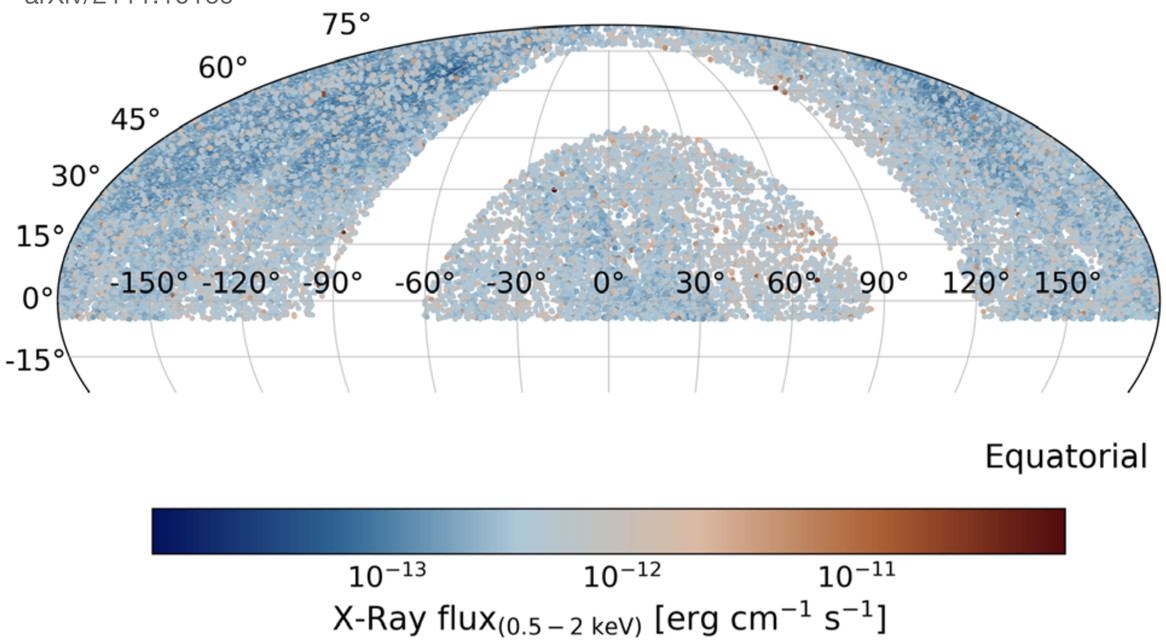


- CRs are accelerated by plasma turbulence in the corona (e.g. K. Murase et al., Y. Inoue et al.)
- **Gamma-rays cascade to the MeV range. No current observational capabilities.**

NEUTRINOS FROM AGN CORES AND IN THE <GEV RANGE

AGN Cores

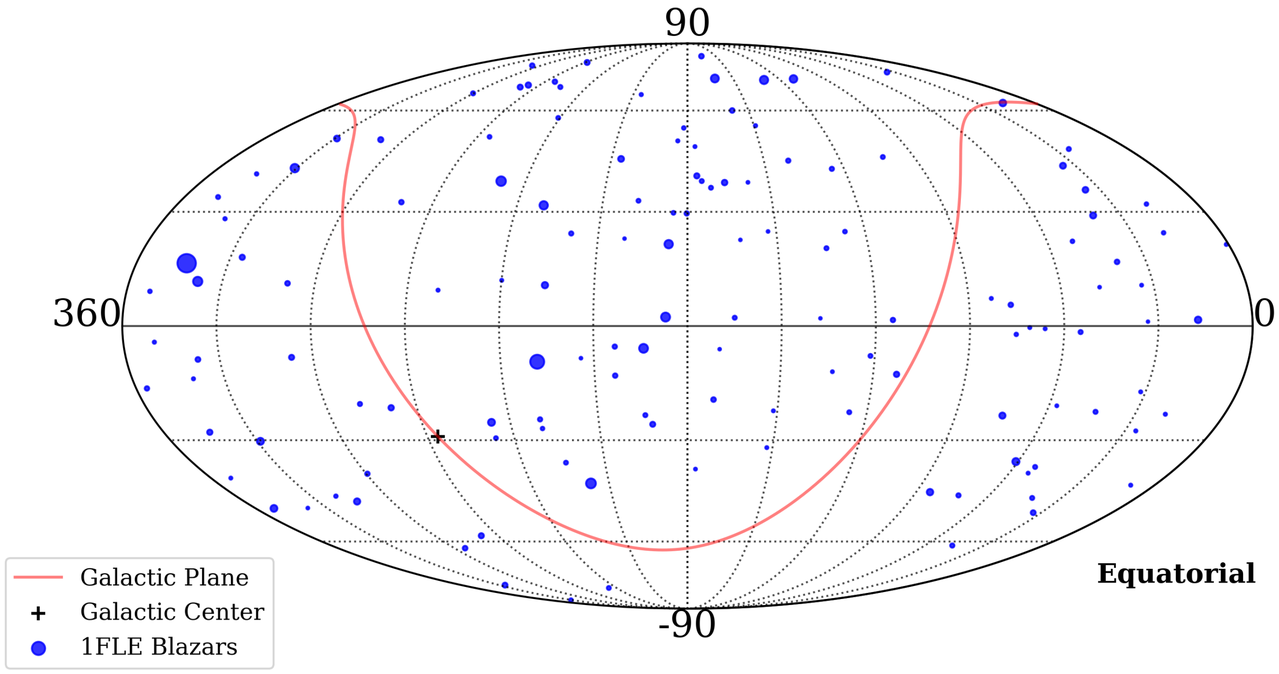
R. Abbasi et al. (IceCube) PRD 106, 022005 (2022)
arXiv/2111.10169



- Search for correlation between accretion disk luminosity for a large AGN sample *O*(10^4). Three selections (IR, radio and LLAGN).
- Soft X-ray, IR and radio observations as proxy for accretion disk luminosity. 2.6σ excess for IR-selected sample.

1FLE Search

R. Abbasi et al. (IceCube) Submitted 2022
arXiv/2207.04946



- Search for neutrinos from Fermi 1FLE blazars (30-100 MeV). Overlap with GeV AGN catalogs.
- No significant detection. Upper limit 1% of the diffuse flux.

NEUTRINOS FROM AGN CORES AND IN THE <GEV RANGE

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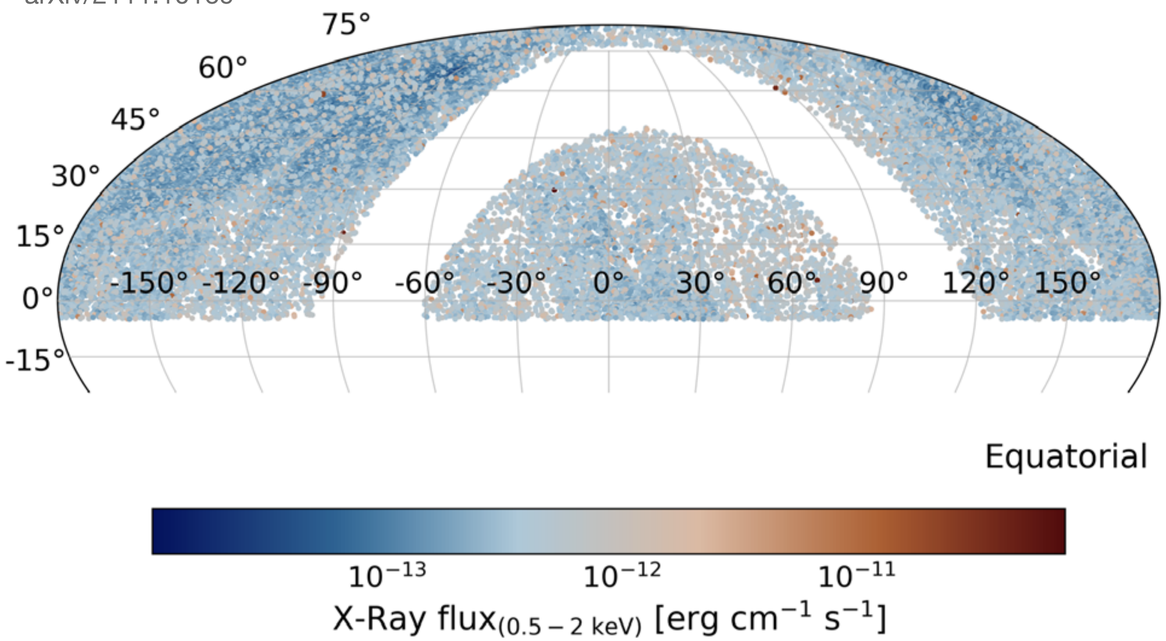

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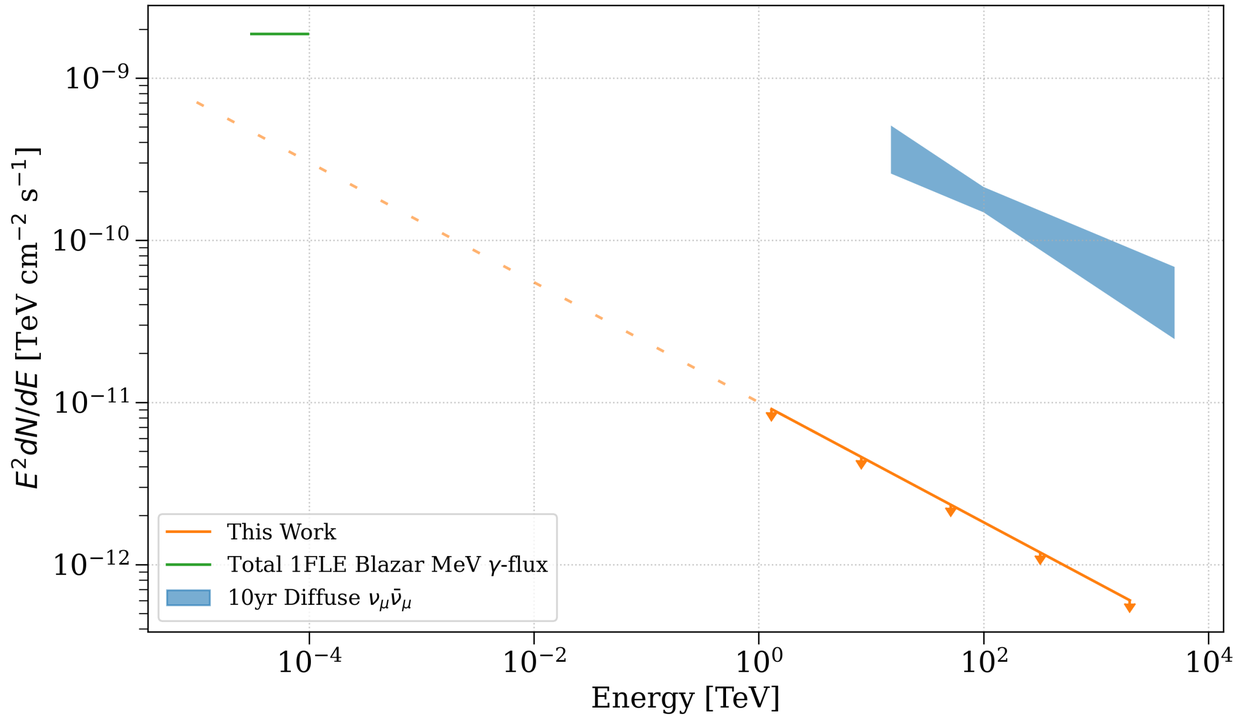
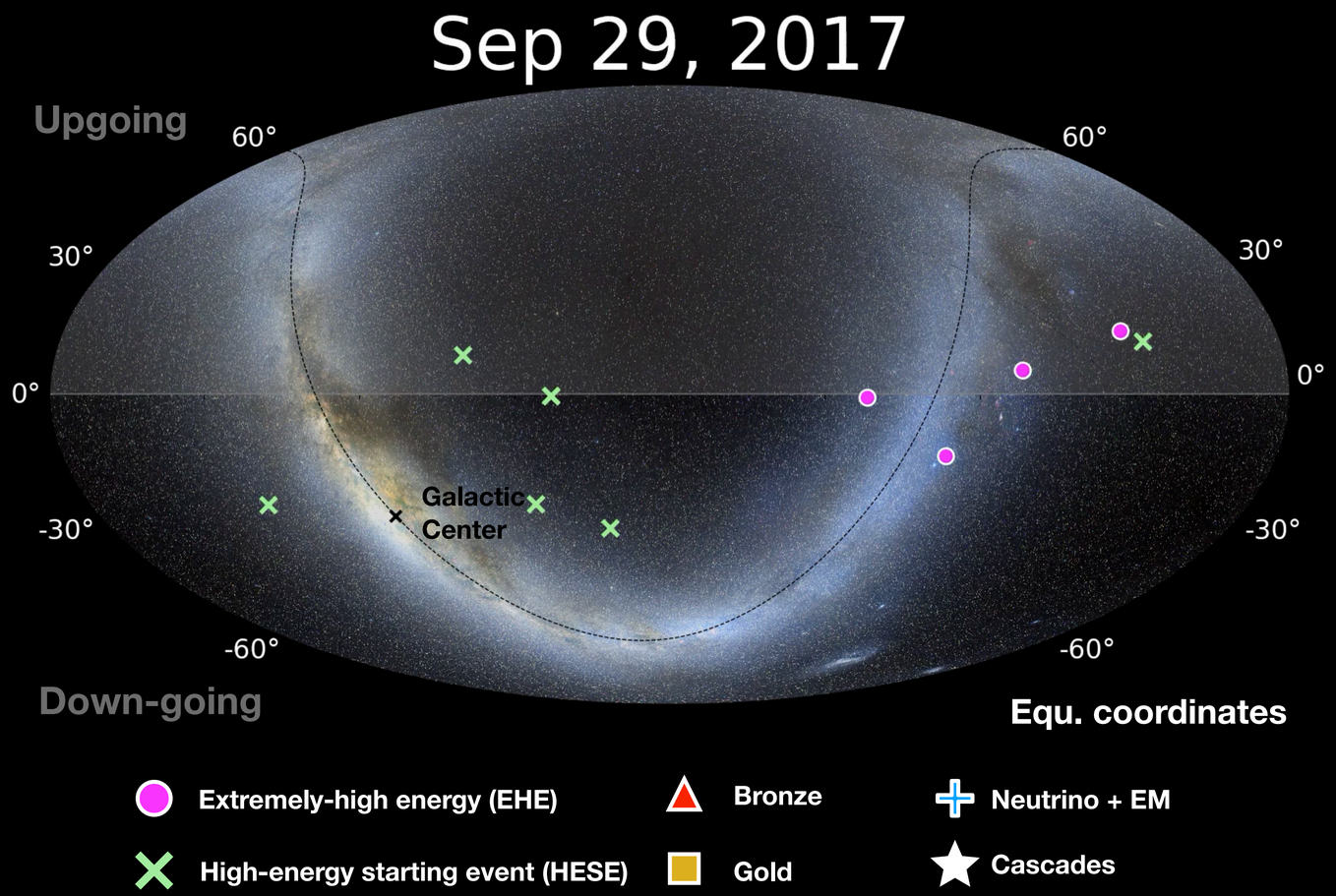


- Search for neutrinos from Fermi 1FLE blazars (30-100 MeV). Overlap with GeV AGN catalogs.
- No significant detection. Upper limit 1% of the diffuse flux.

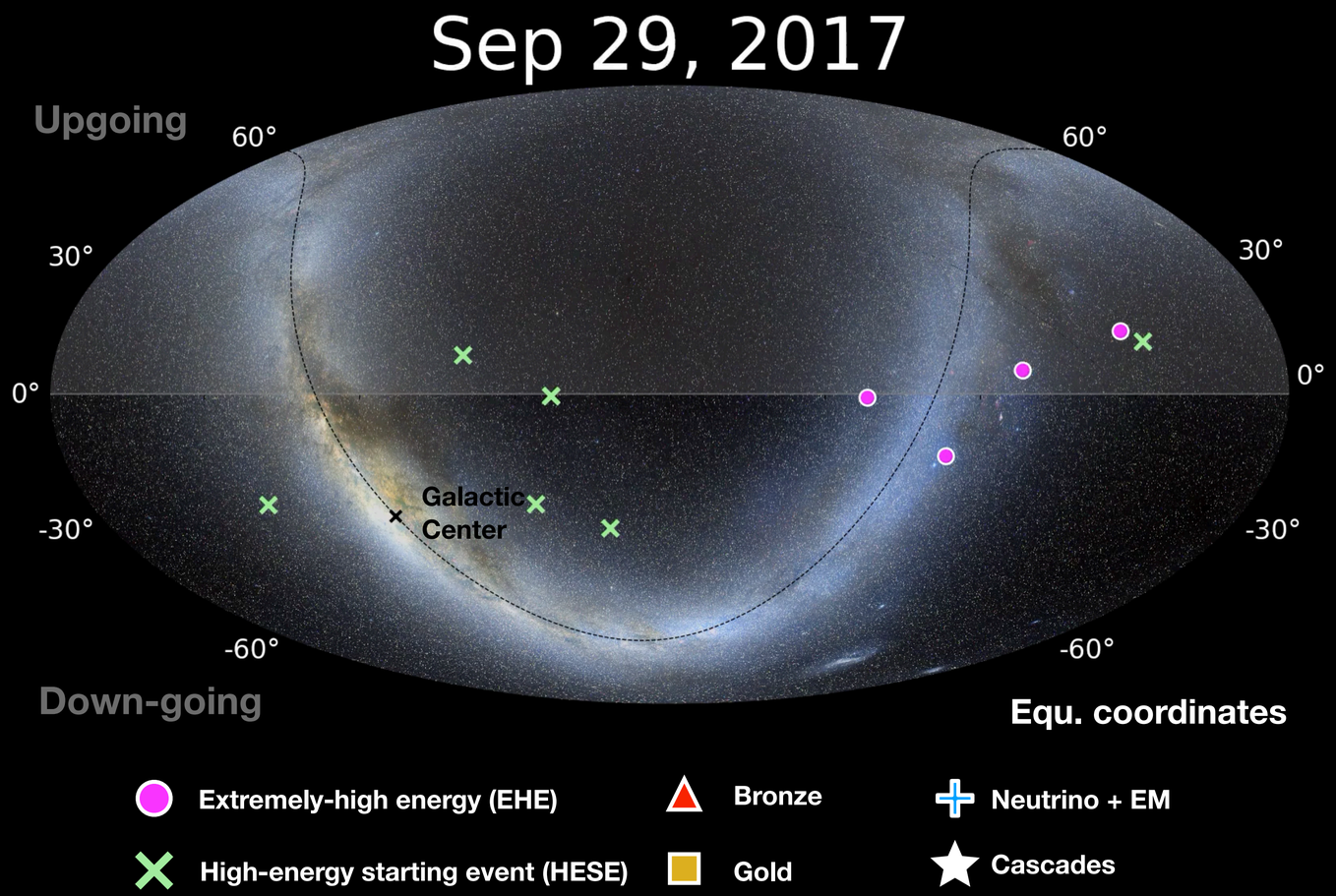
TAKE-AWAY POINTS FOR STEADY AGN EMISSION

- No dominant contribution from gamma-ray bright blazars. Opaque sources?
- Several correlations have been claimed at the ~3**σ** level, including the Seyfert galaxy NGC 1068.
- Neutrino AGN may instead be bright in the X-ray to MeV range, where **observational capabilities are currently lacking**.

REALTIME NEUTRINO ALERTS



REALTIME NEUTRINO ALERTS



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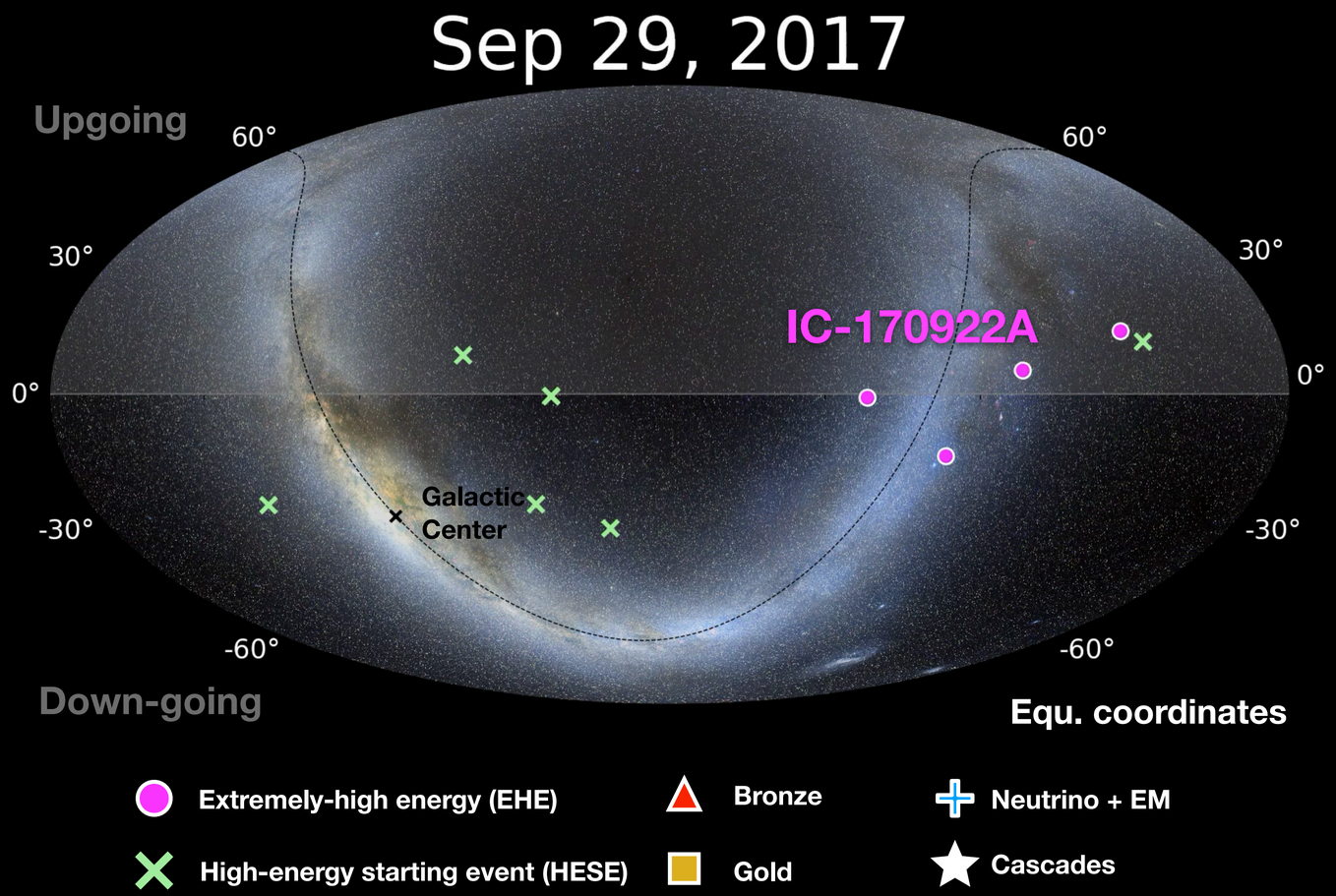
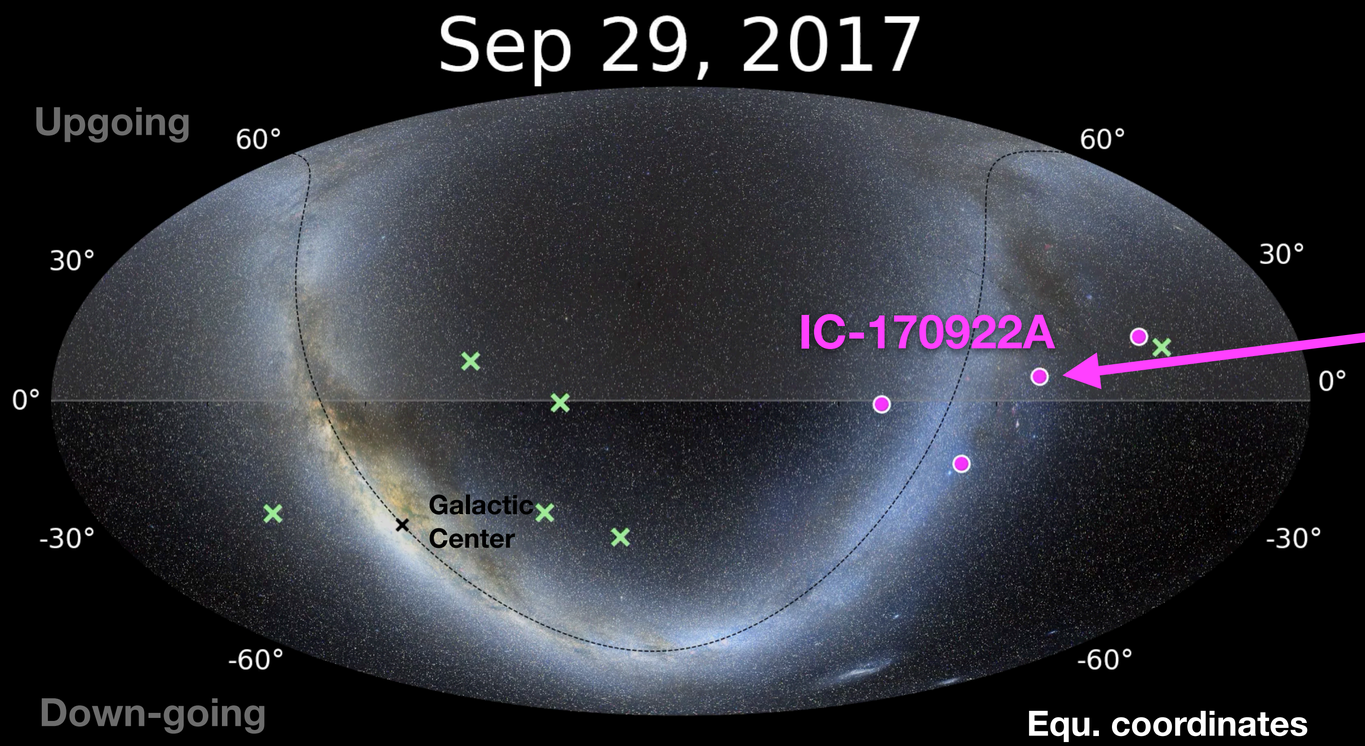
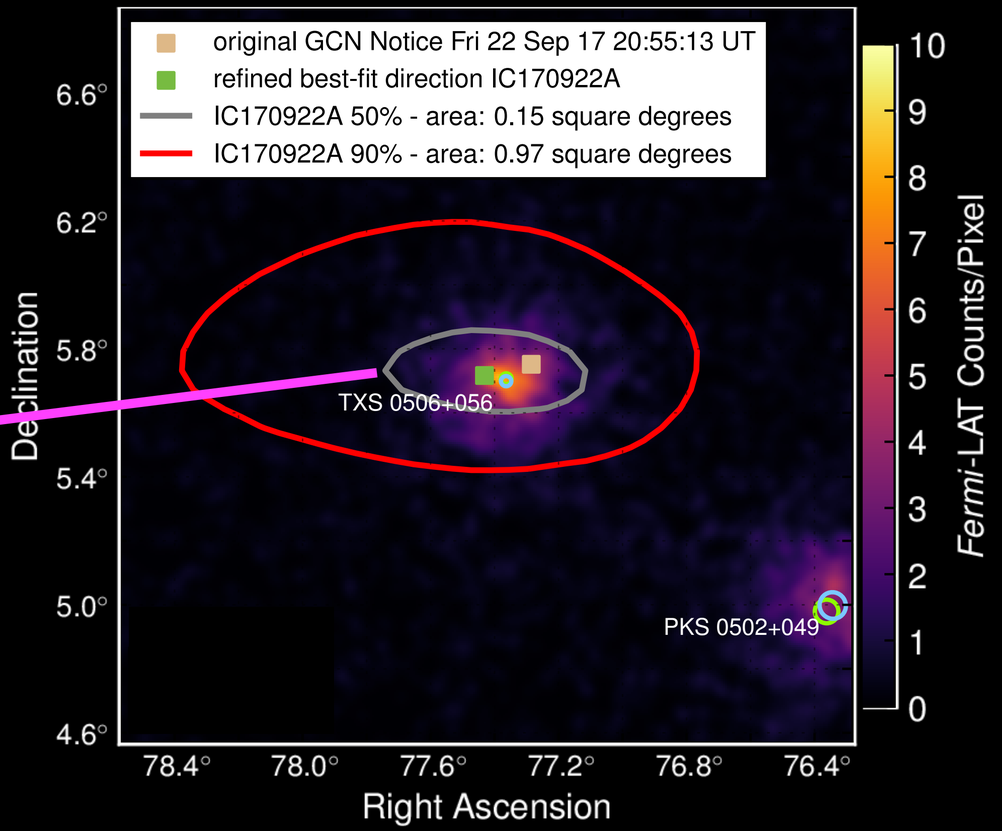


REALTIME NEUTRINO ALERTS

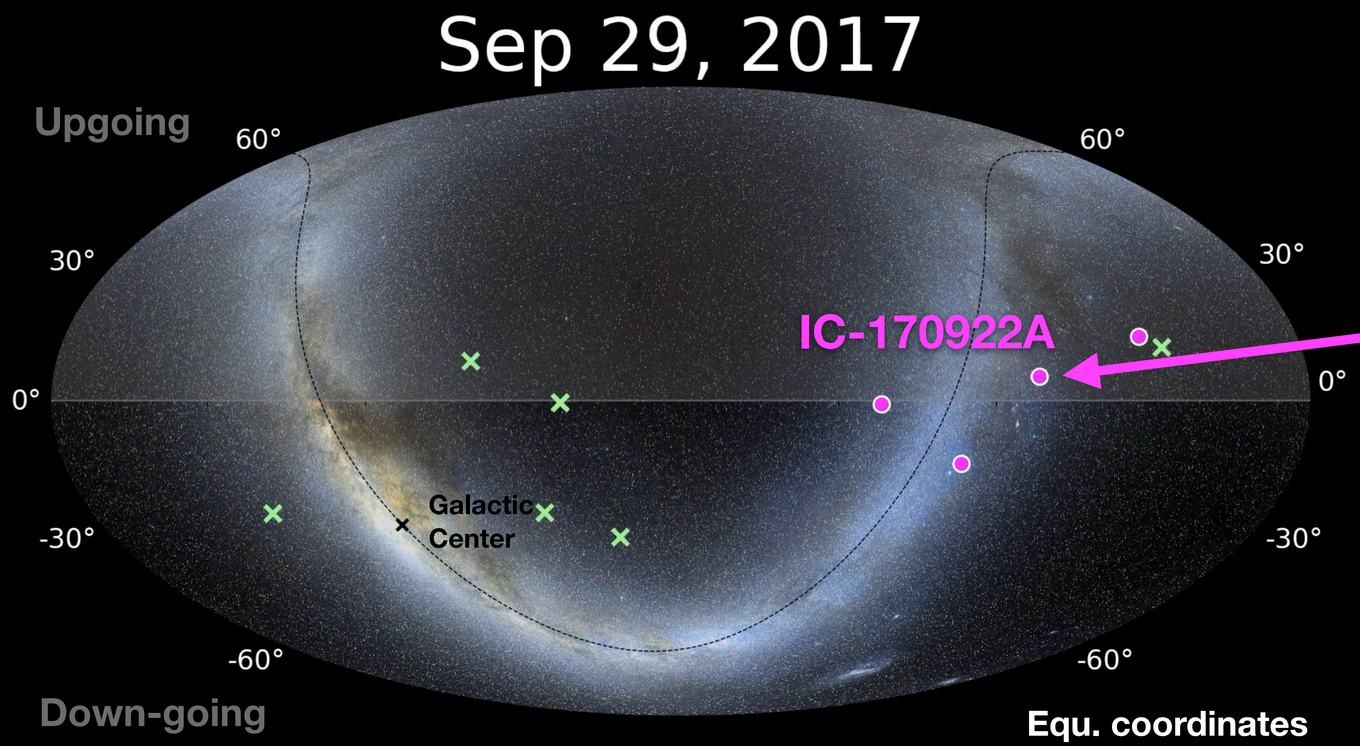


Extremely-high energy (EHE)
High-energy starting event (HESE)
Bronze
Gold
Neutrino + EM
Cascades

Fermi-LAT
0.1 - 300 GeV



REALTIME NEUTRINO ALERTS



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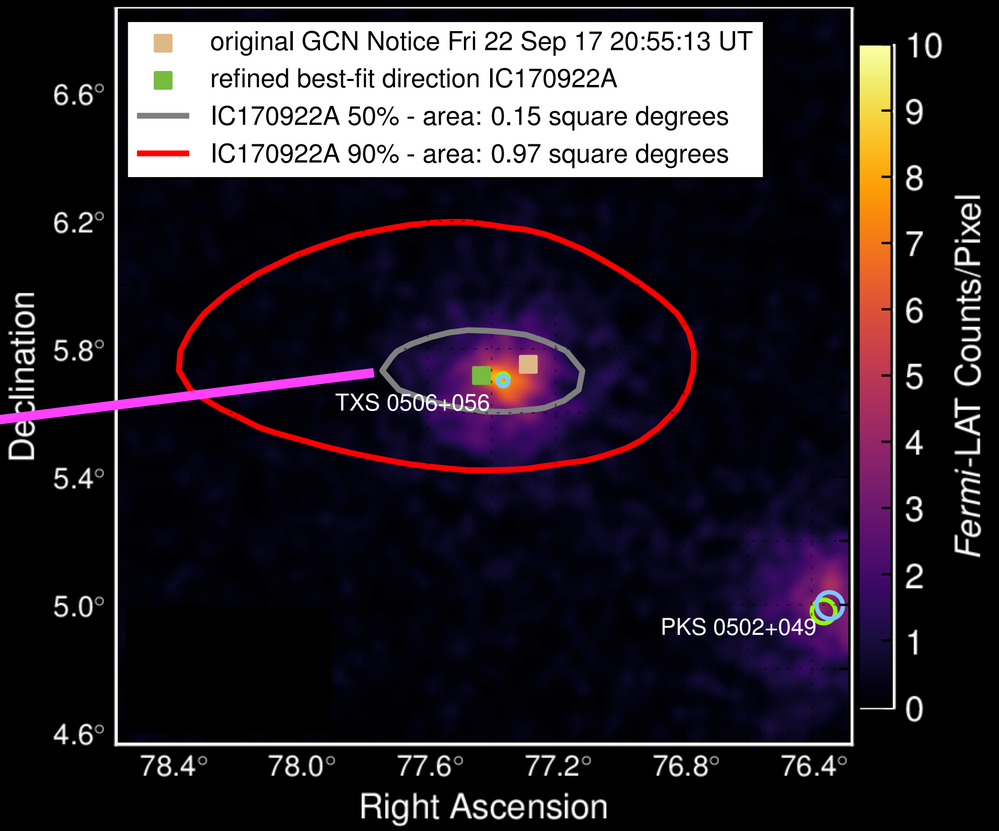
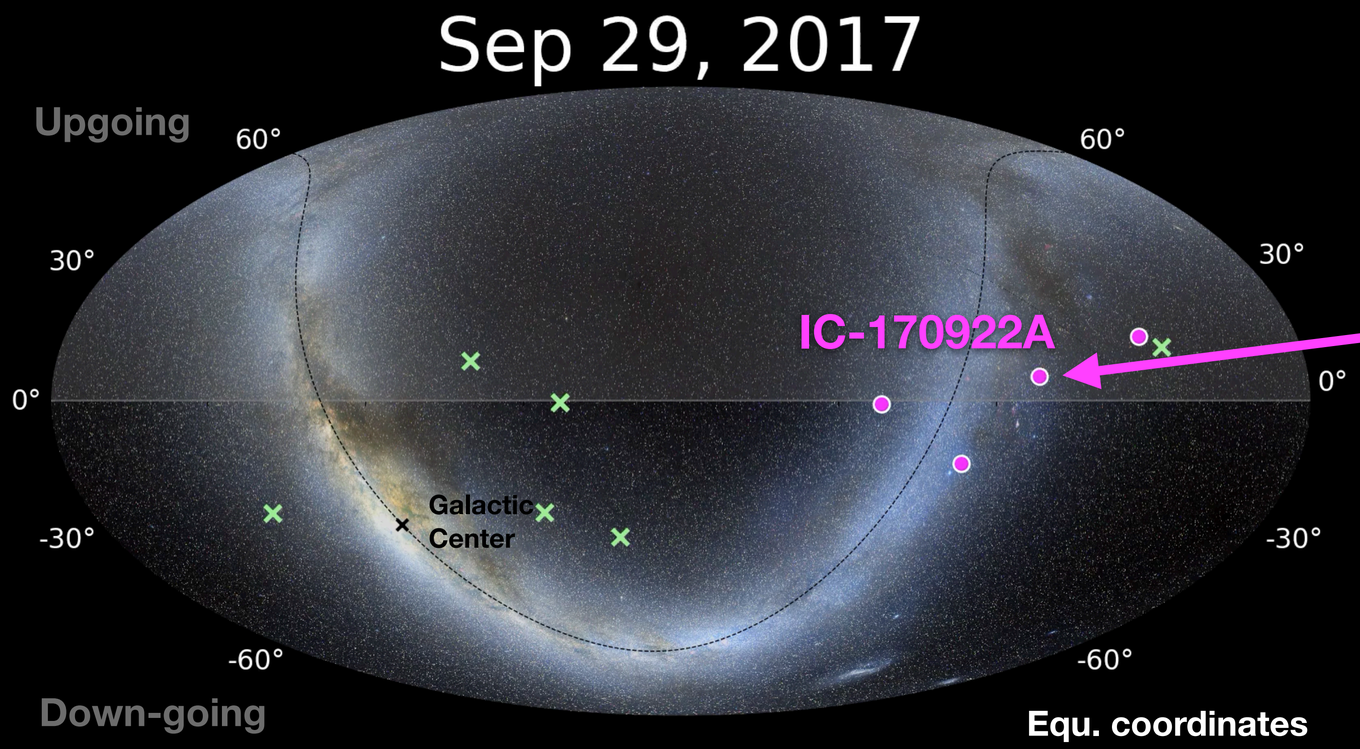
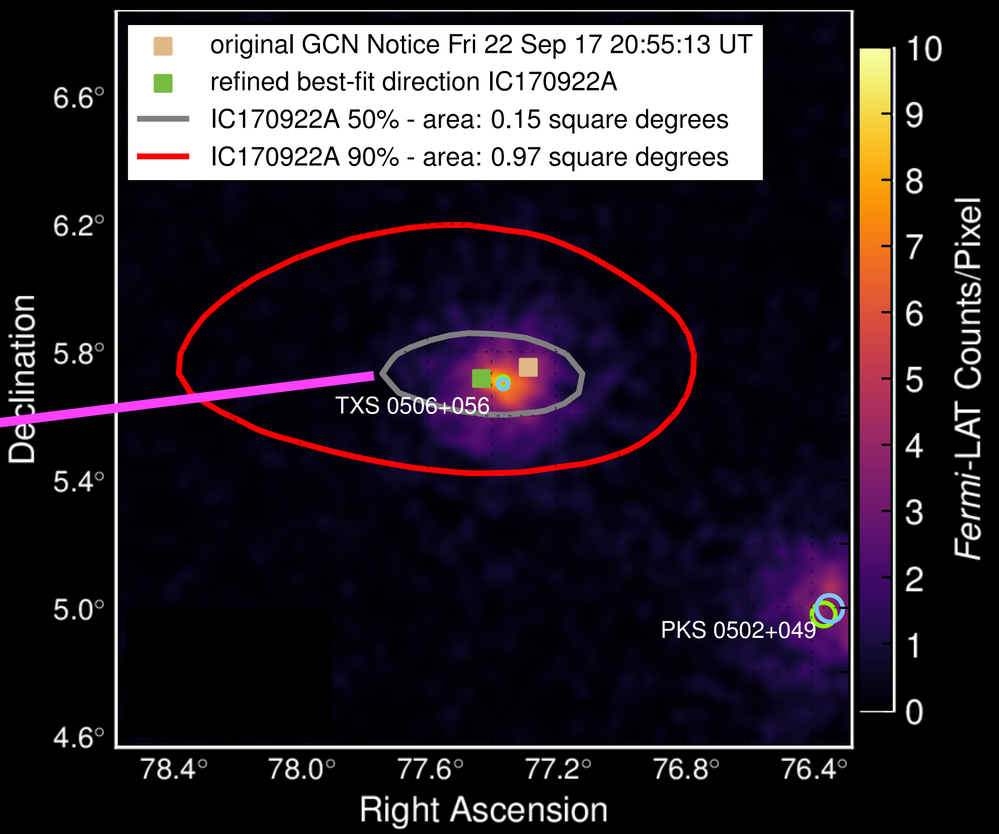


- IceCube-170922A: 290 TeV neutrino energy

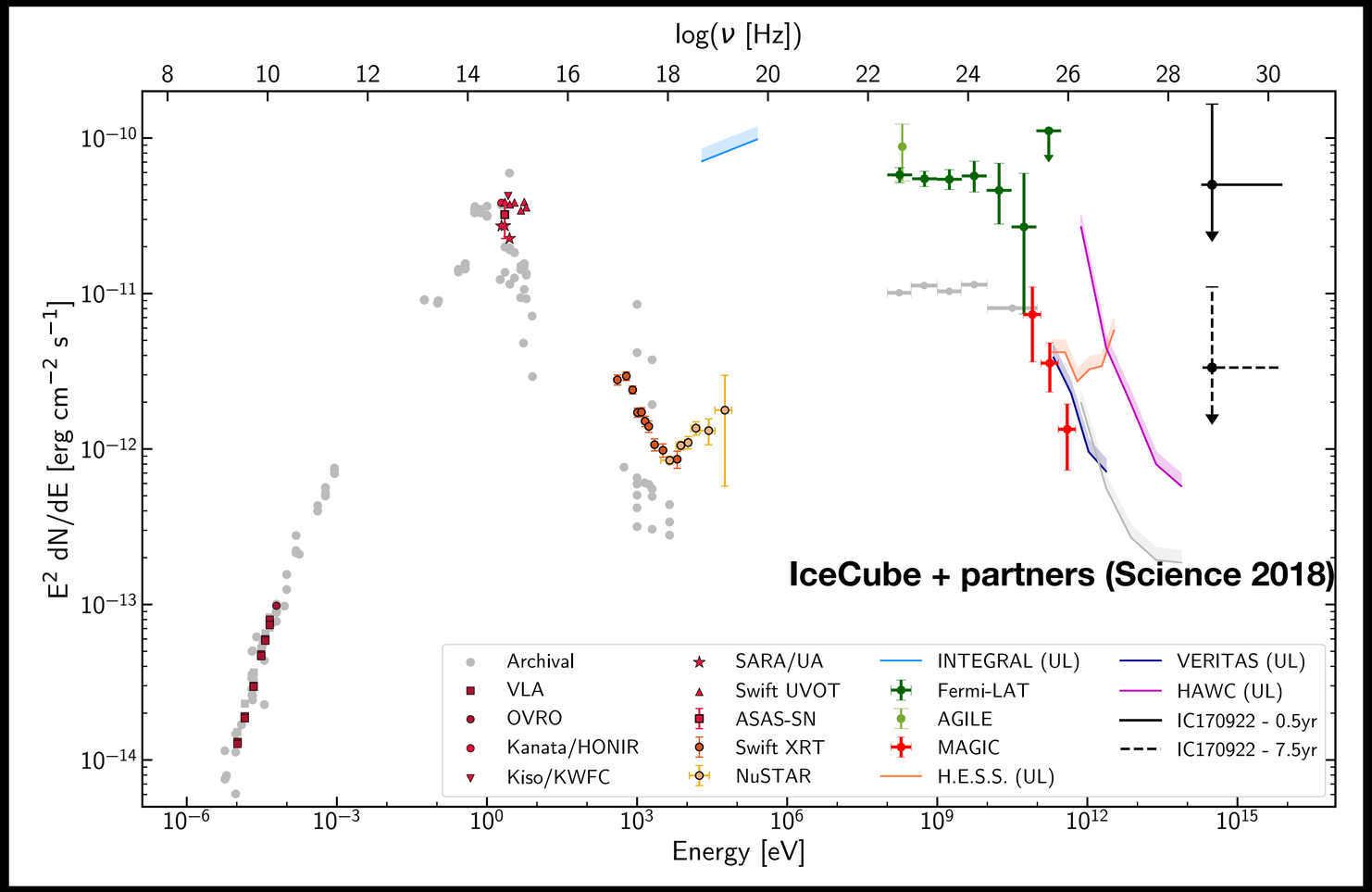
REALTIME NEUTRINO ALERTS

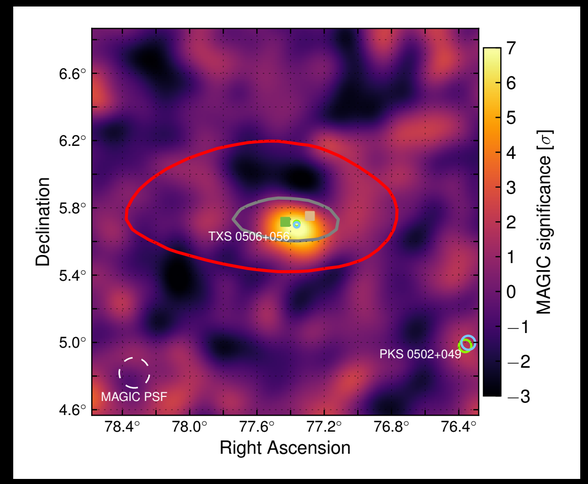




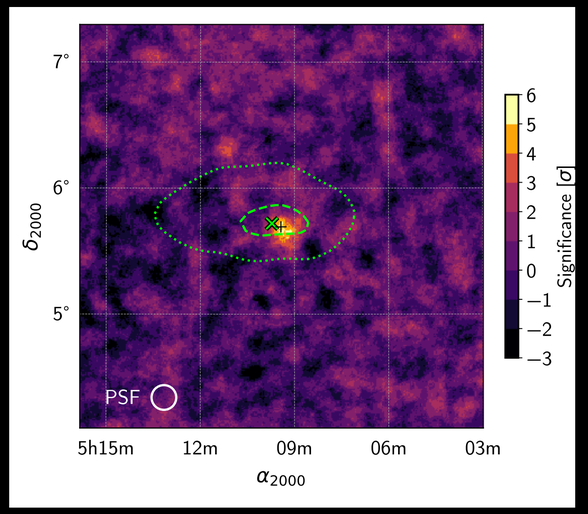
- IceCube-170922A: 290 TeV neutrino energy
- Correlated with flaring, hard-spectrum gamma-ray blazar **TXS 0506+056** (3σ). Additional neutrino emission in 2014-2015.

PHOTONS FROM TXS 0506+056





MAGIC (ApJL 2018)



VERITAS (ApJL 2018)

- TXS 0506+056: *Fermi* blazar at z=0.34. Broad multi-wavelength follow-up campaign, led to the detection of the source >100 GeV by ground-based gamma-ray instruments.
- **3σ chance coincidence correlation. Evidence for a connection between TXS 0506+056 and IC170922A.**

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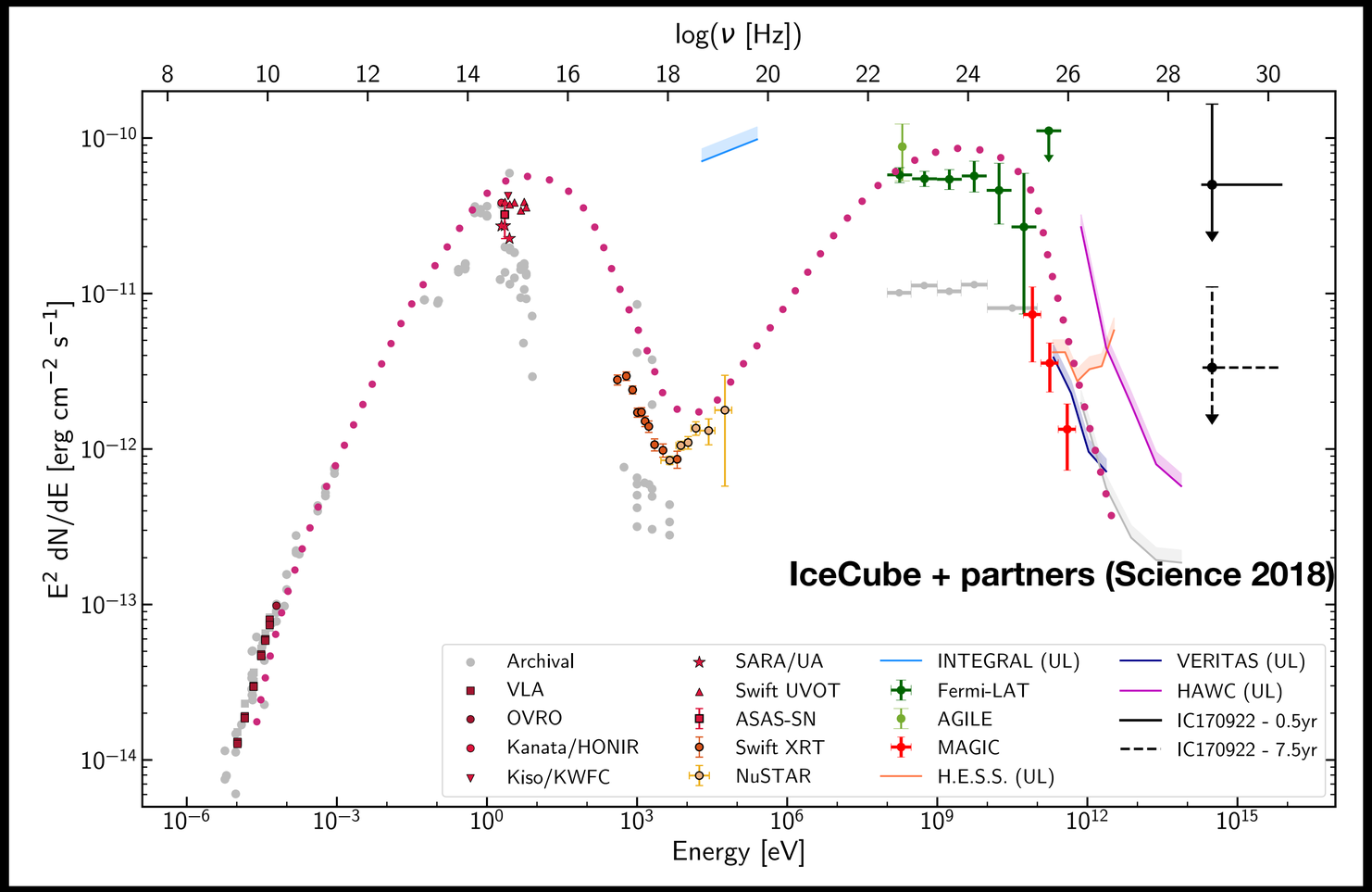

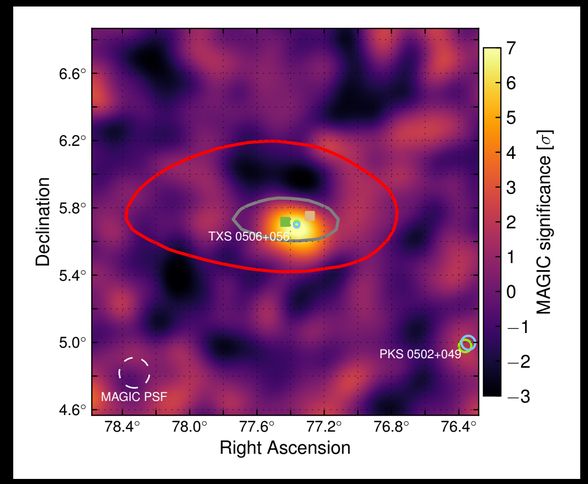

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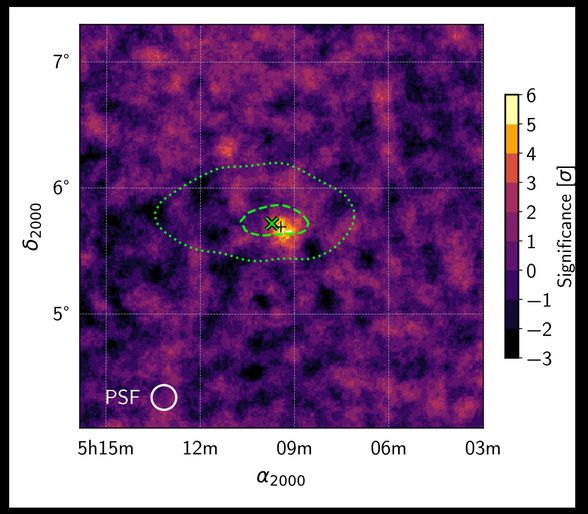

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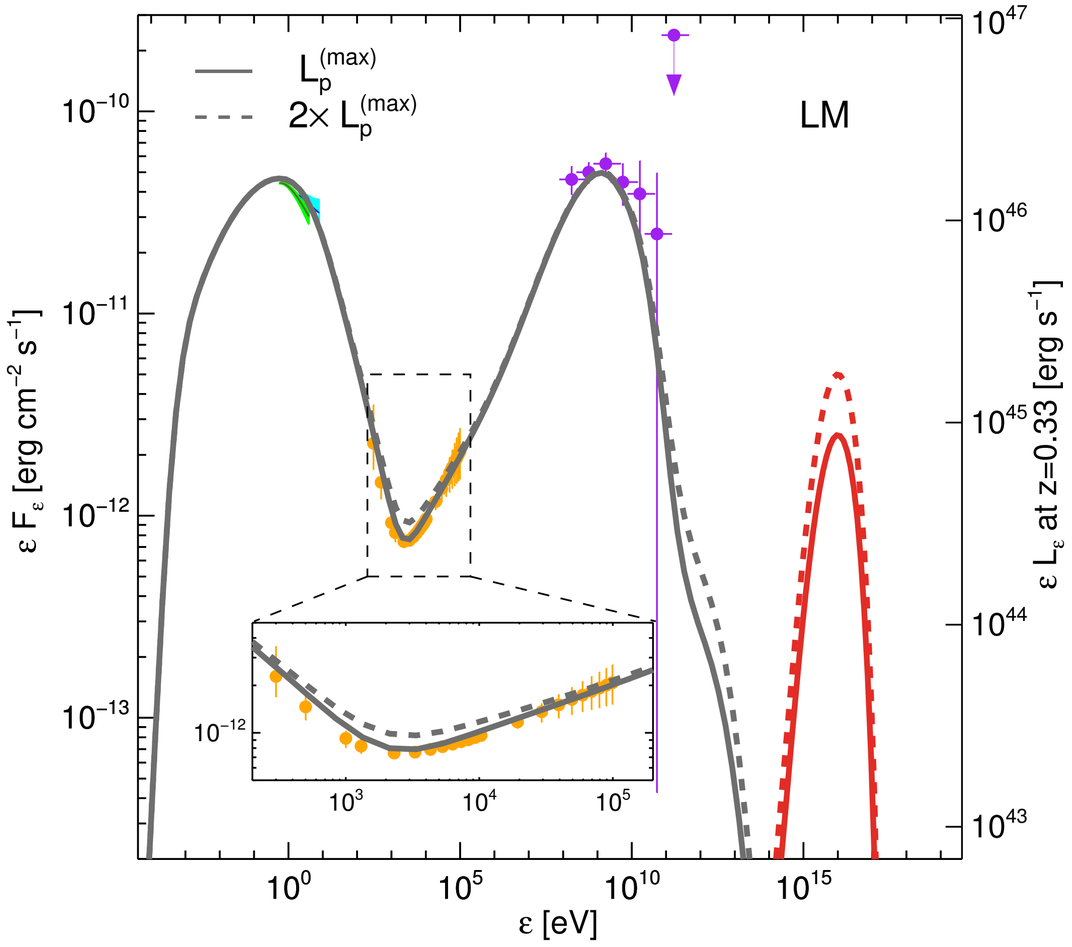
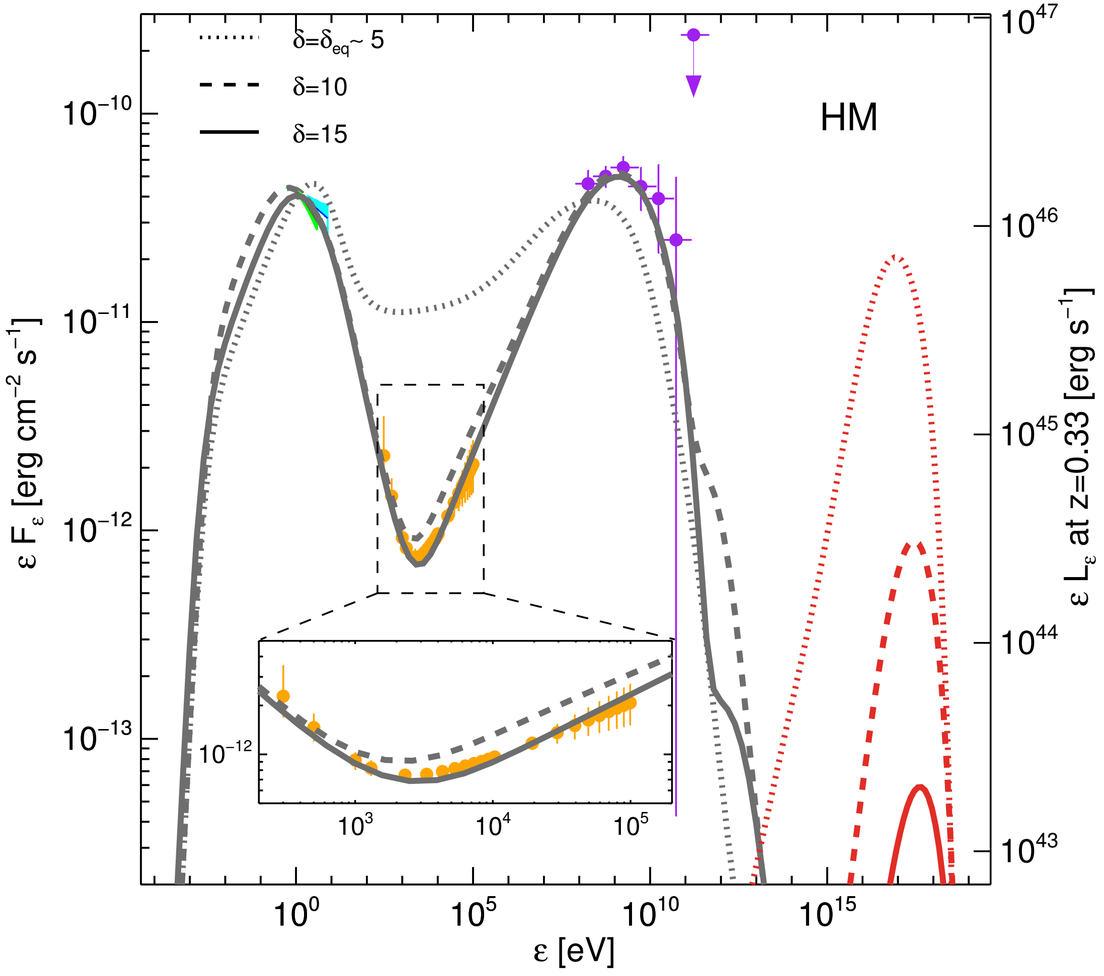
MODELING THE 2017 NEUTRINO EMISSION

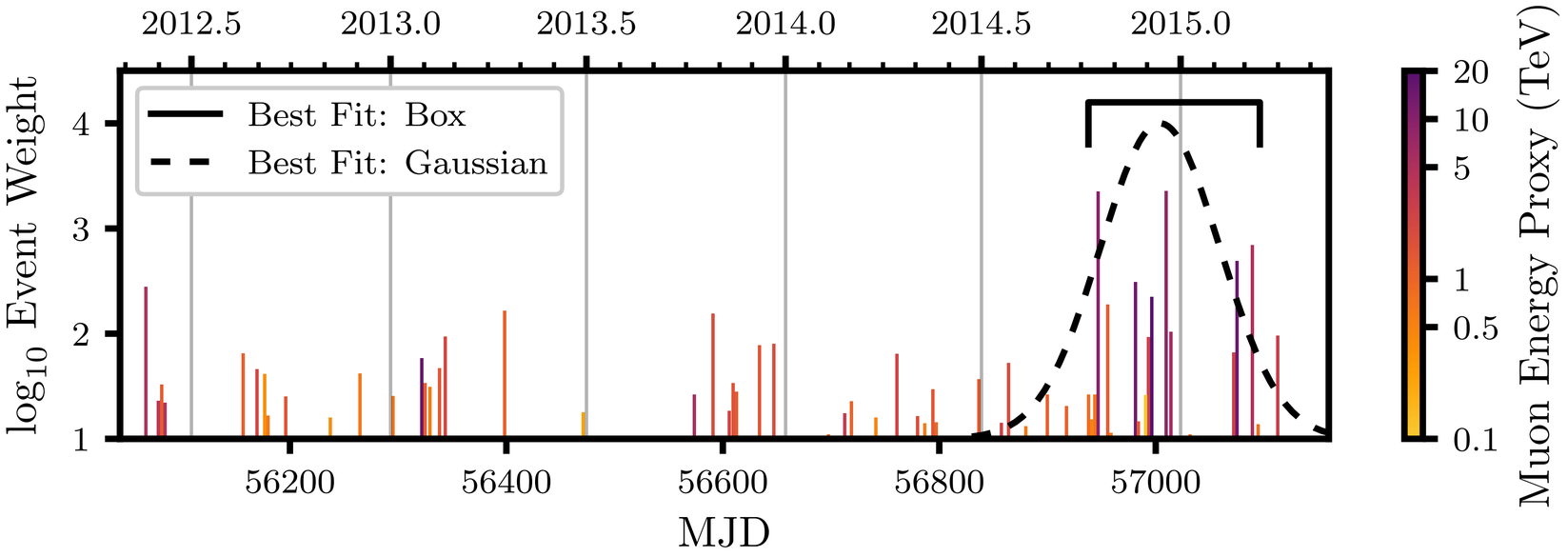
Keivani et al. (arXiv/1807.04537)
among many others

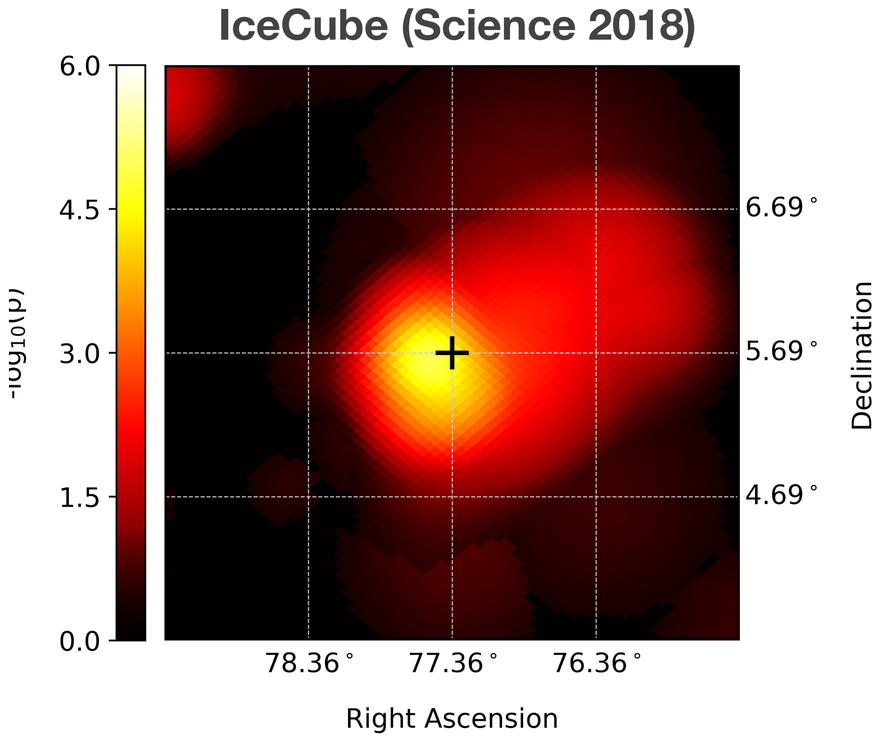




- **Strong constraints on hadronic emission from X-ray observations.**

ARCHIVAL NEUTRINO EVENTS FROM ICECUBE





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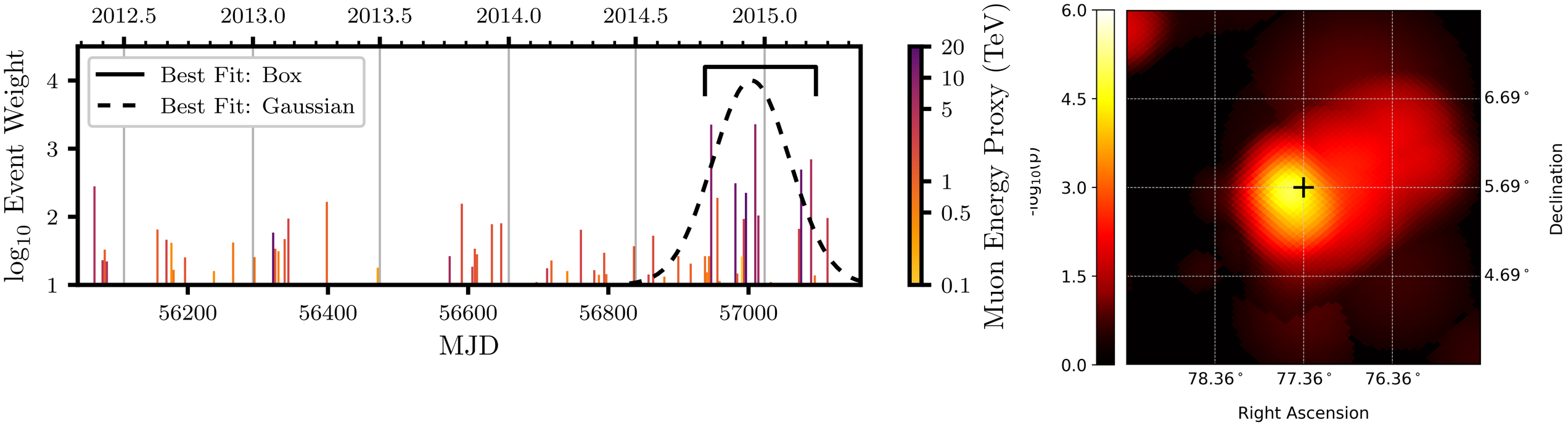
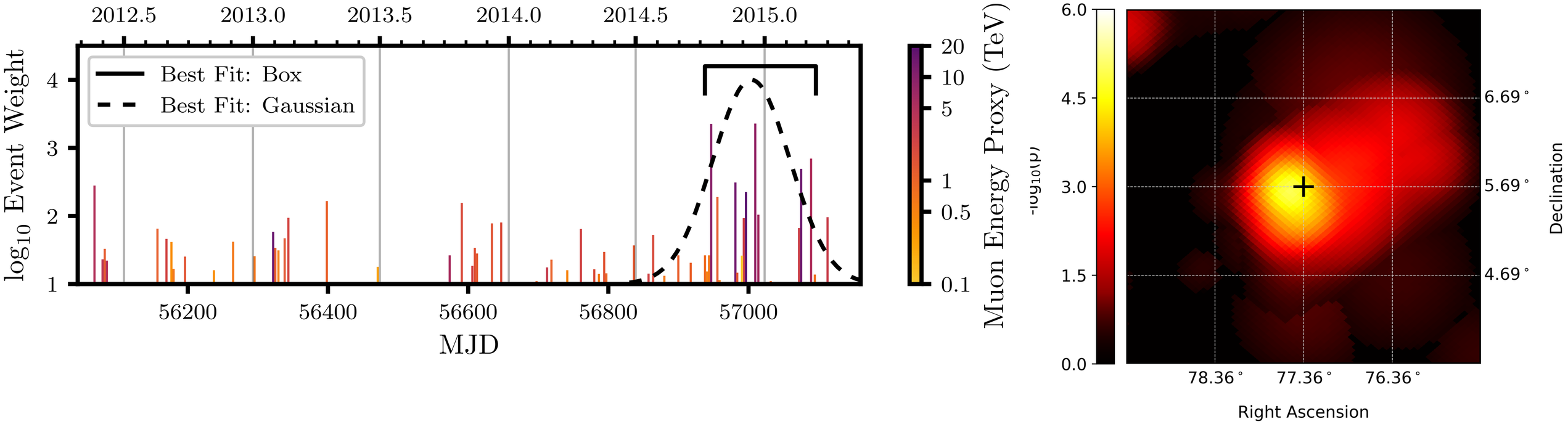


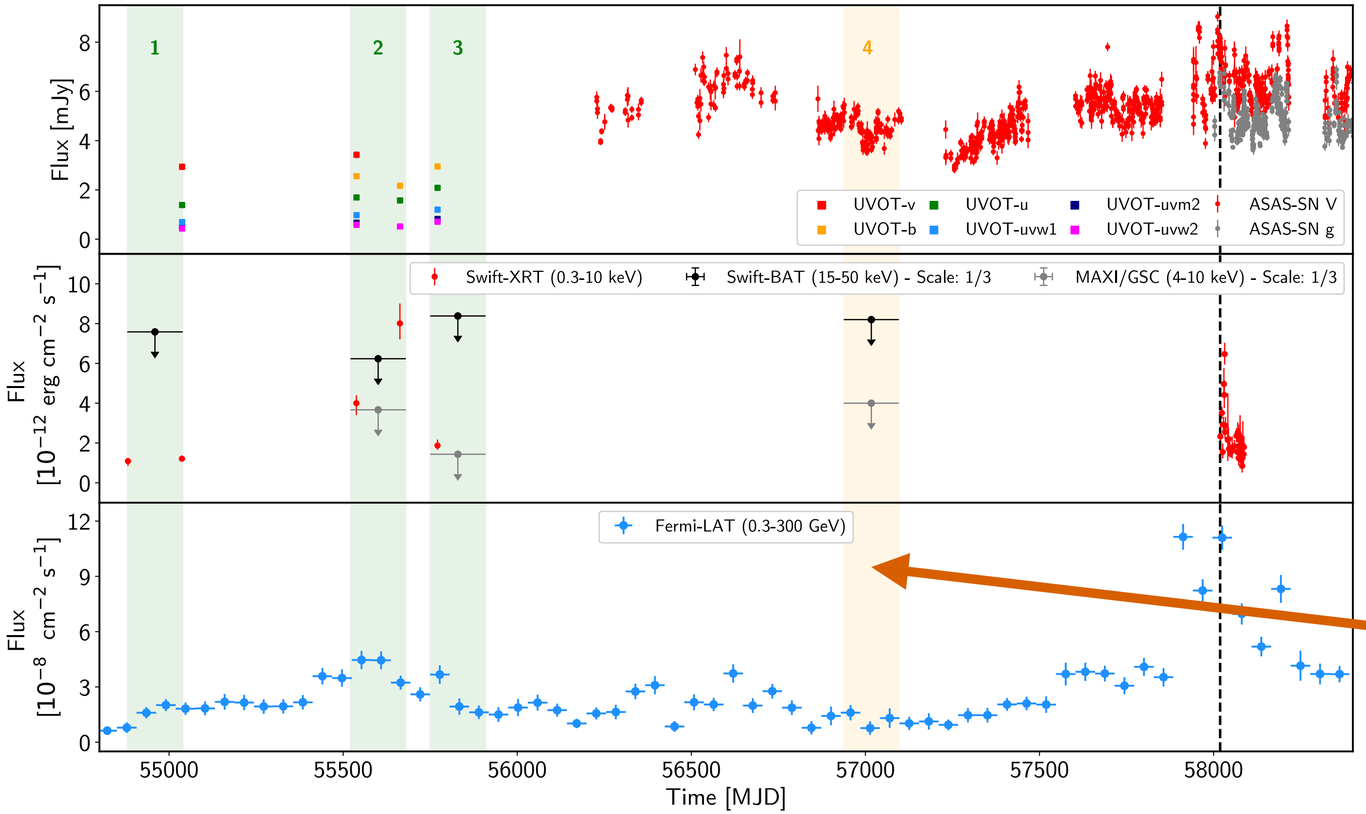
- Archival analysis revealed a **13±5 neutrino excess (3.5σ)** in 2014-2015 over 110 days.

ARCHIVAL NEUTRINO EVENTS FROM ICECUBE

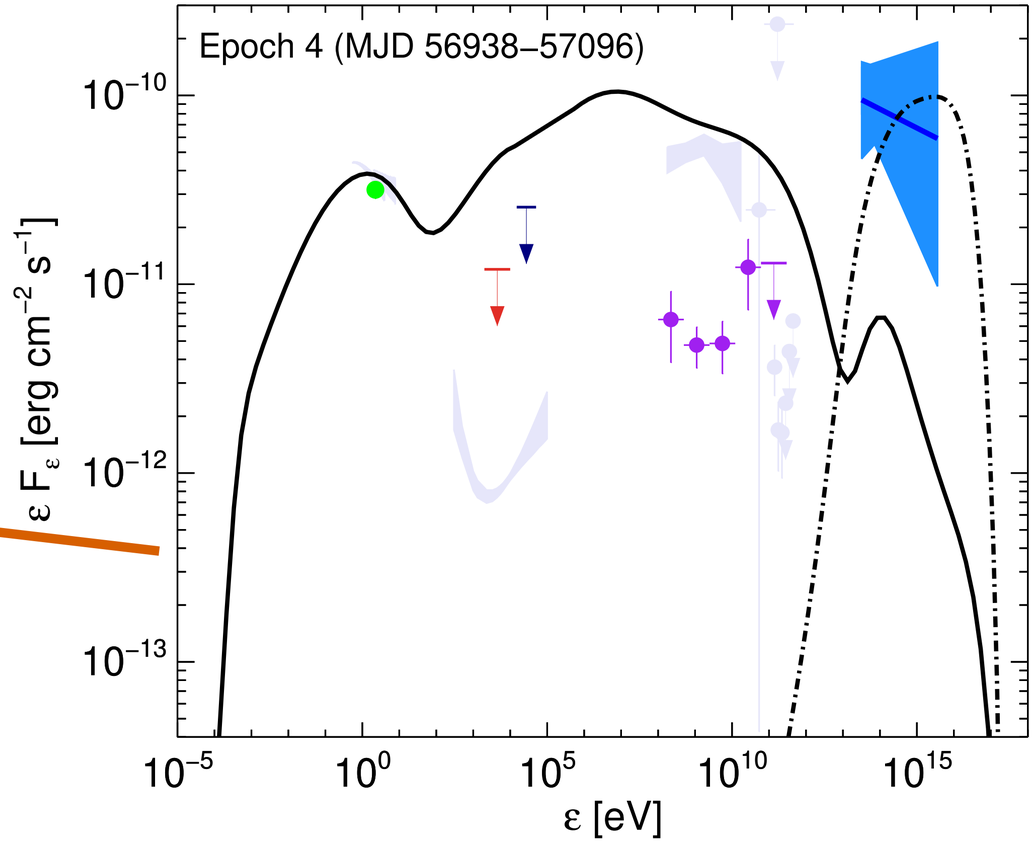


- Archival analysis revealed a **13±5 neutrino excess (3.5σ)** in 2014-2015 over 110 days.
- No follow-up campaign. **What's happening on the EM side?**

EM EMISSION FROM TXS 0506+056 AROUND THE FLARE



Petropoulou, Murase, MS, ++ (2019)



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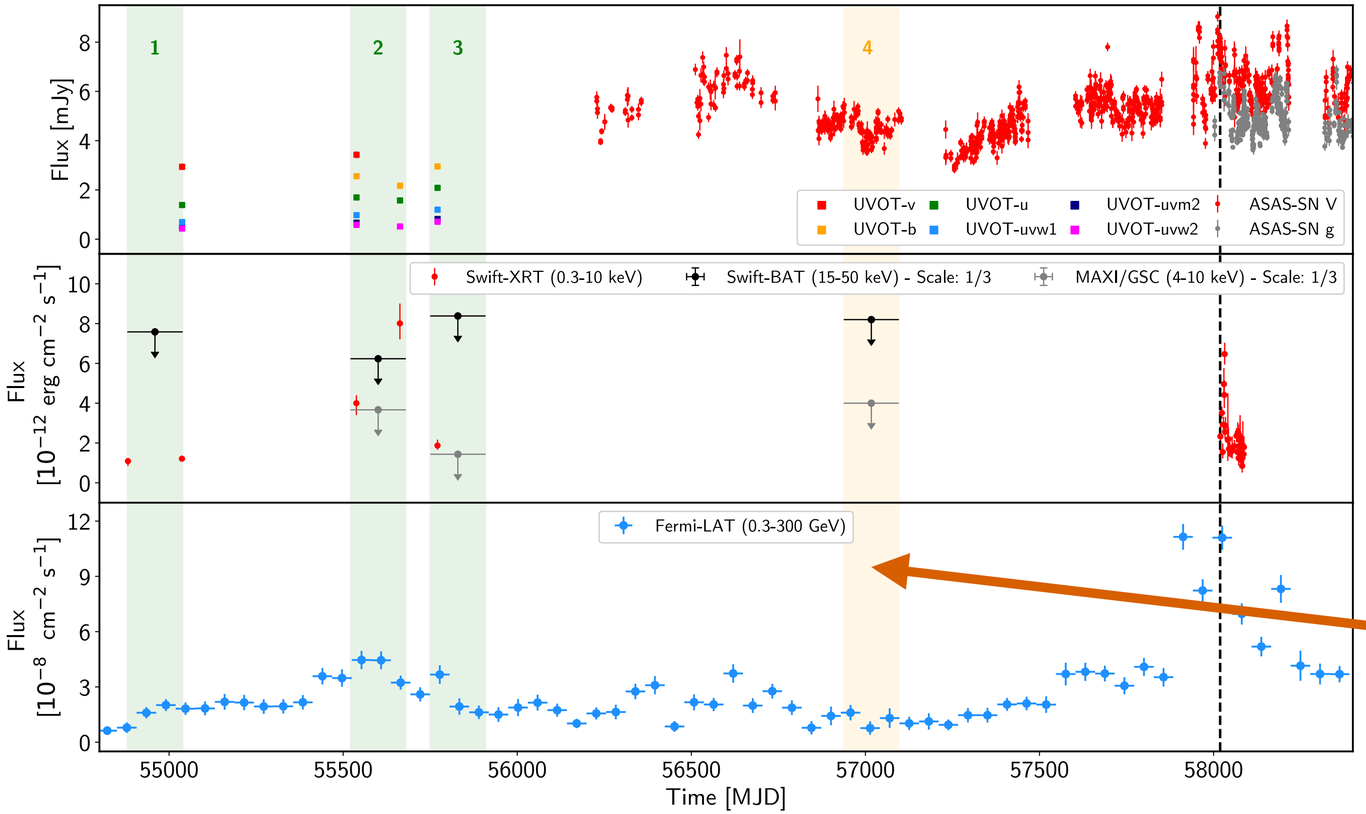

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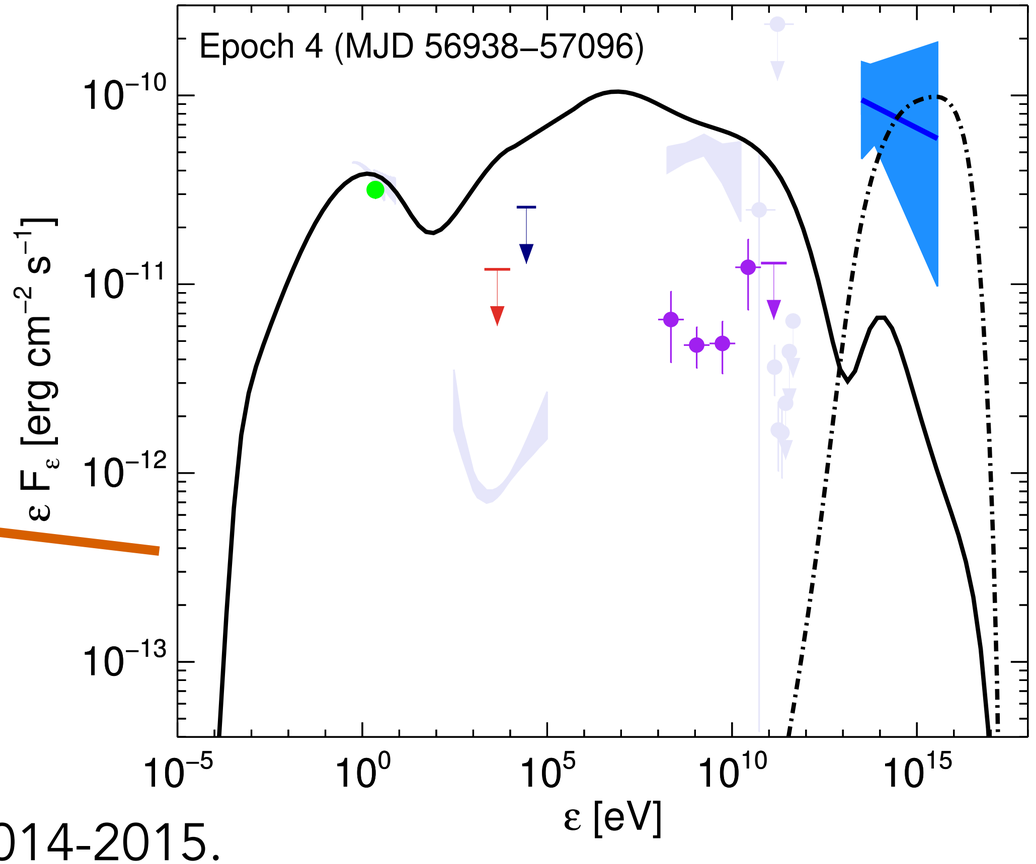

- No evidence for EM flaring activity from the source in 2014-2015.
- **Most models over-predict the X-ray to gamma fluxes.**
- Multi-messenger follow ups with be crucial in the coming decade.

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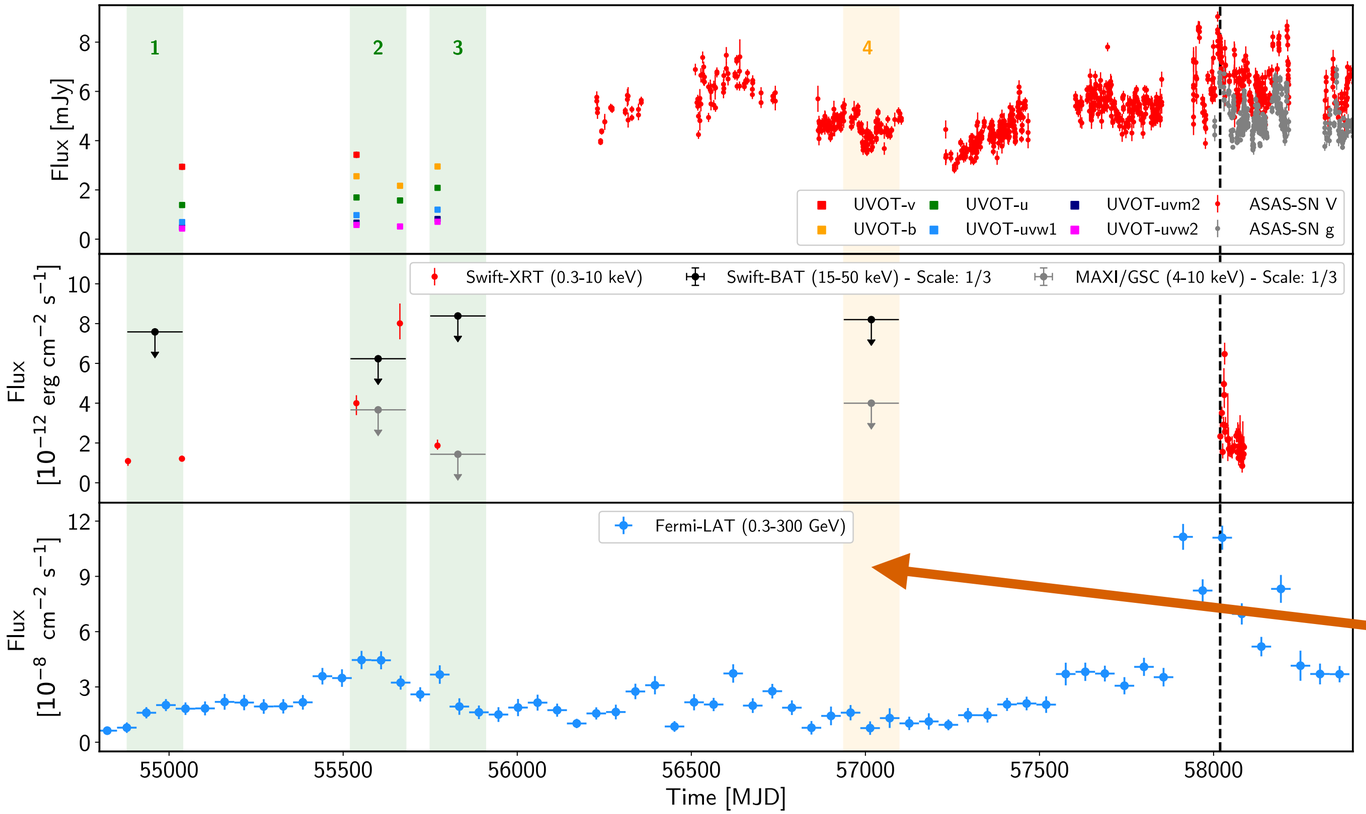

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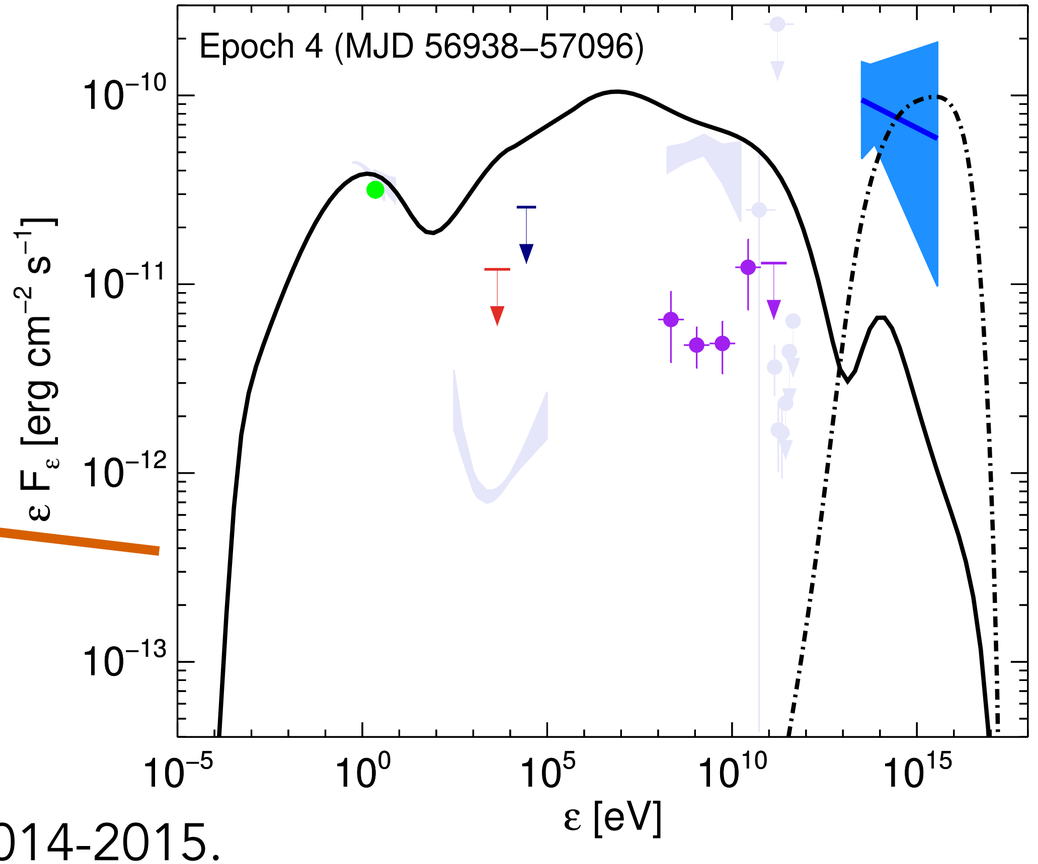

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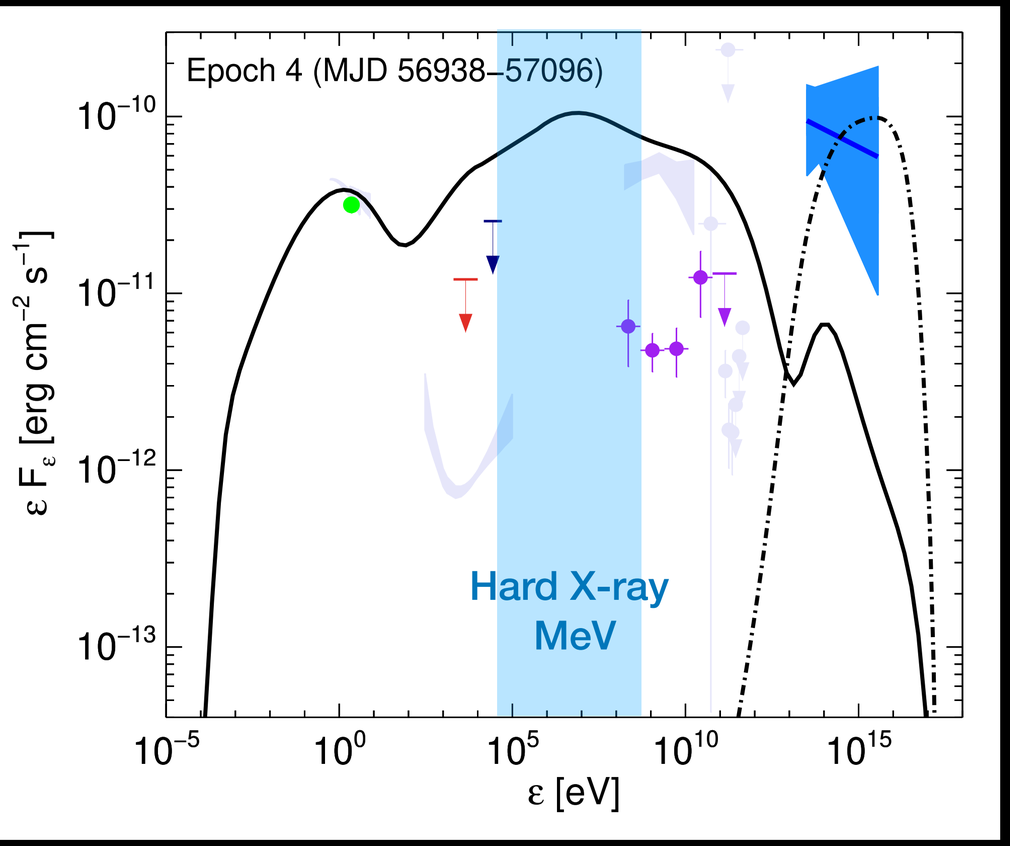
- **Most models over-predict the X-ray to gamma fluxes.**
- Multi-messenger follow ups with be crucial in the coming decade.

Many modeling efforts for 2014-15/17: Reimer+ 2019, Cerruti+ 2018, Zhang+ 2018, Keivani 2018+, Petropoulou+ 2019

MAIN CHALLENGES FOR NEUTRINO STUDIES OF AGN



Neutrinos

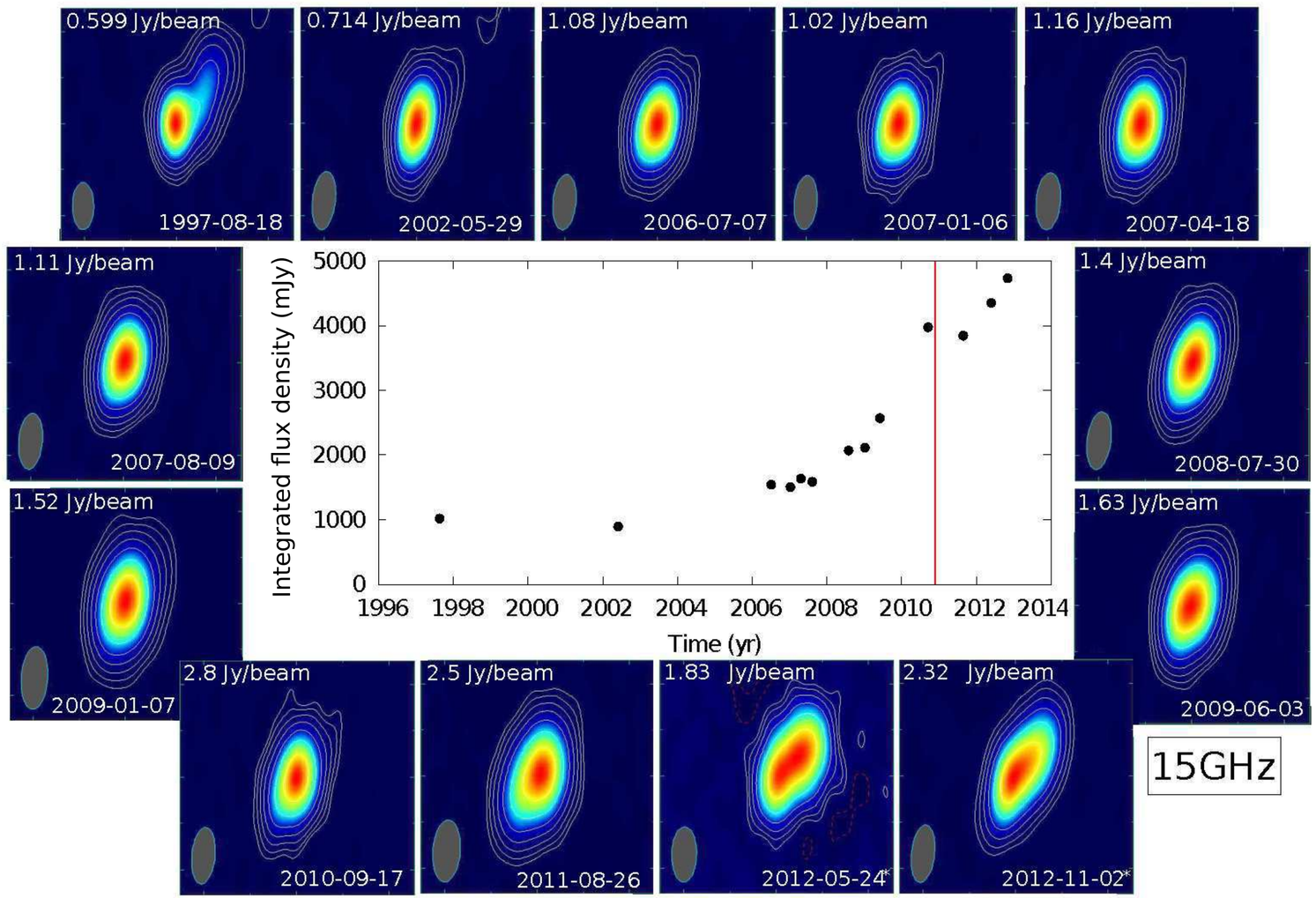
- Neutrino rates are low (IceCube provides O(10) events / year at > 100 TeV.
- Angular resolution is poor (~0.5 - 1 deg) limiting association studies.

EM

- Limited sky coverage with sufficient sensivity.
- No coverage is some critical energy bands (hard X-ray to MeV, VHE)

OTHER EXAMPLES

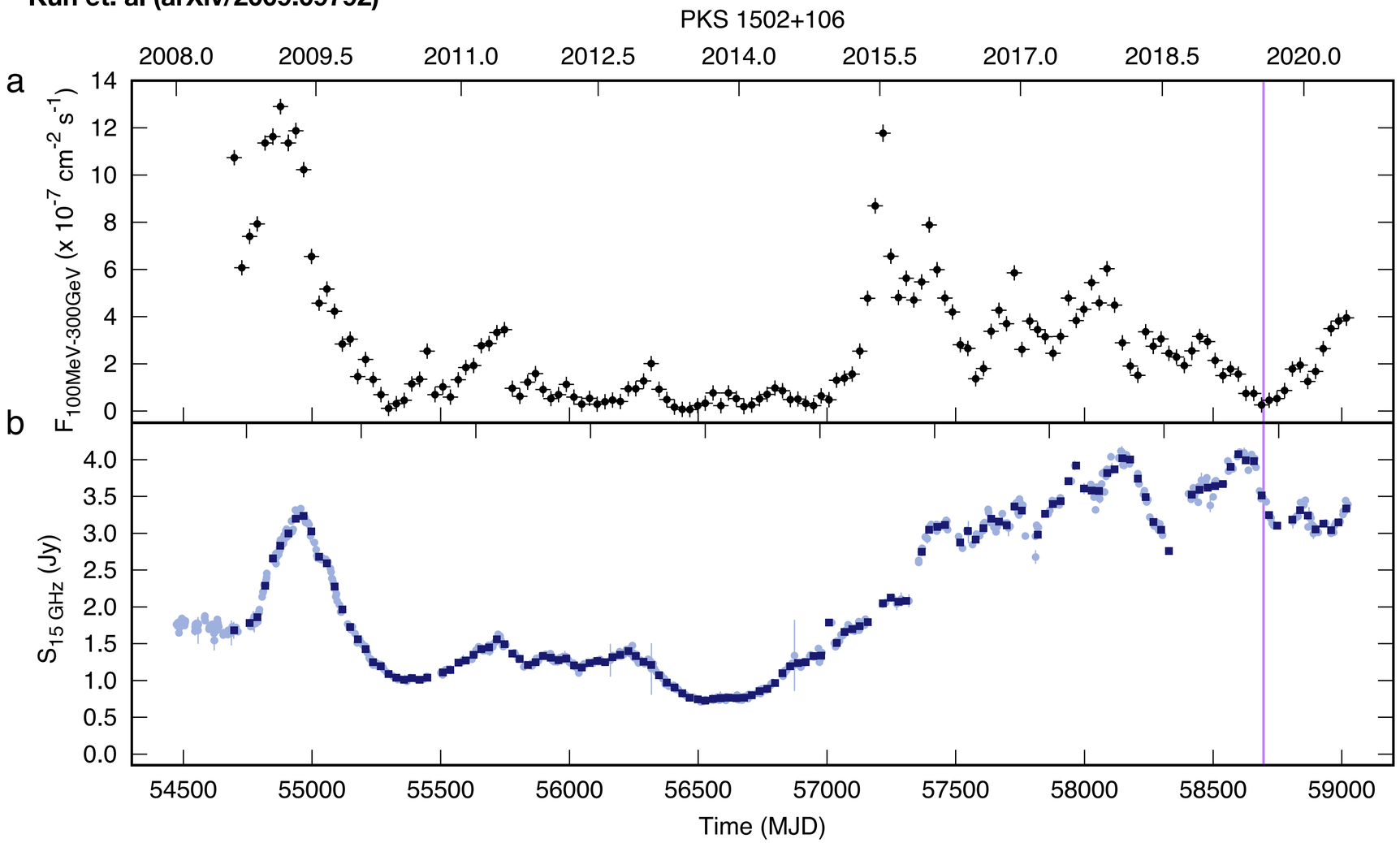
Kun et. al (arXiv/1607.04041)



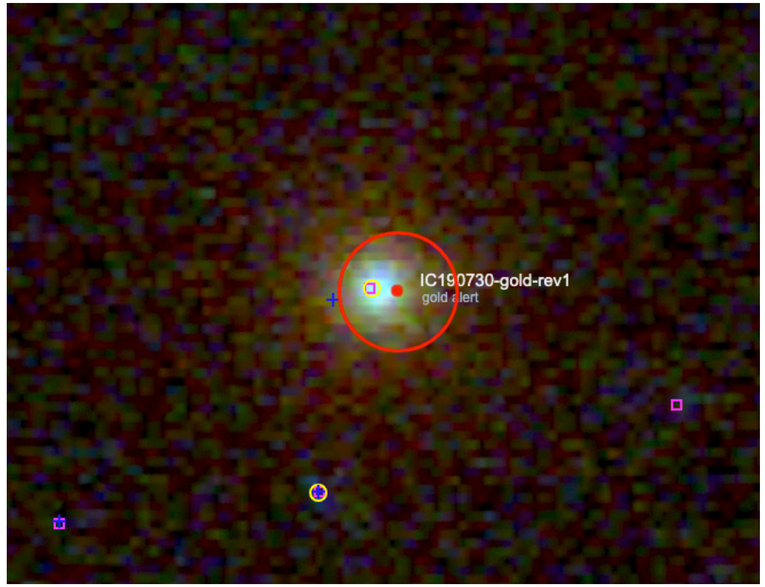
- FSRQ PKS 0723–008 in the region of an high-energy neutrino track.
- MOJAVE light curve shows steady flux increase around the time of the neutrino event.

PKS 1502+106

Kun et. al (arXiv/2009.09792)



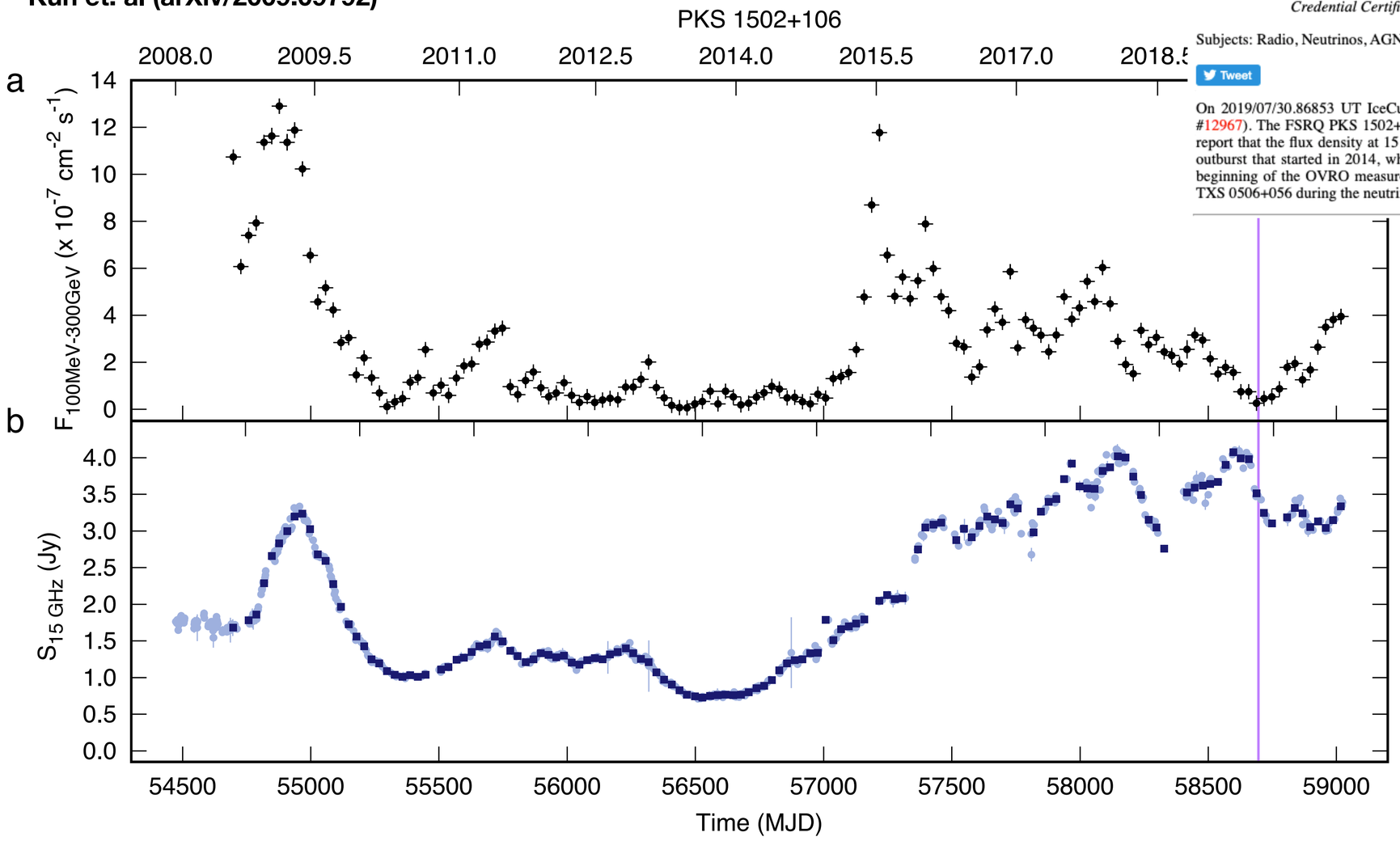
- Neutrino event on July 30th, 2019
- Among the brightest FSRQs.



Neutrino emission during gamma-ray low-state?

PKS 1502+106

Kun et. al (arXiv/2009.09792)



[Previous | Next | ADS]

Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)*
on 7 Aug 2019; 12:31 UT
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

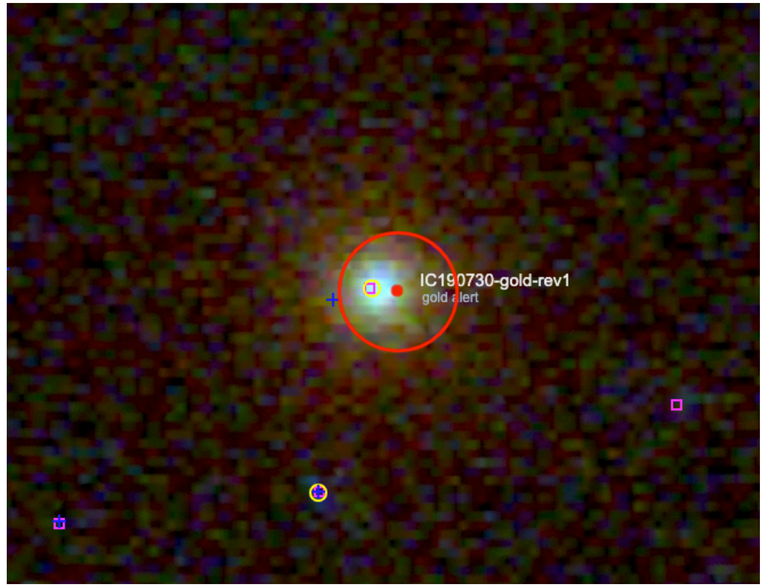
Tweet

On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.

Related

12996	Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
12985	IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
12983	Optical fluxes of candidate neutrino blazar PKS 1502+106
12981	ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A
12974	Optical follow-up of IceCube-190730A with ZTF
12971	IceCube-190730A: MASTER alert observations and analysis
12967	IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106
12926	VLA observations reveal increasing brightness of 1WHSP J104516.2+275133, a potential source of IC190704A

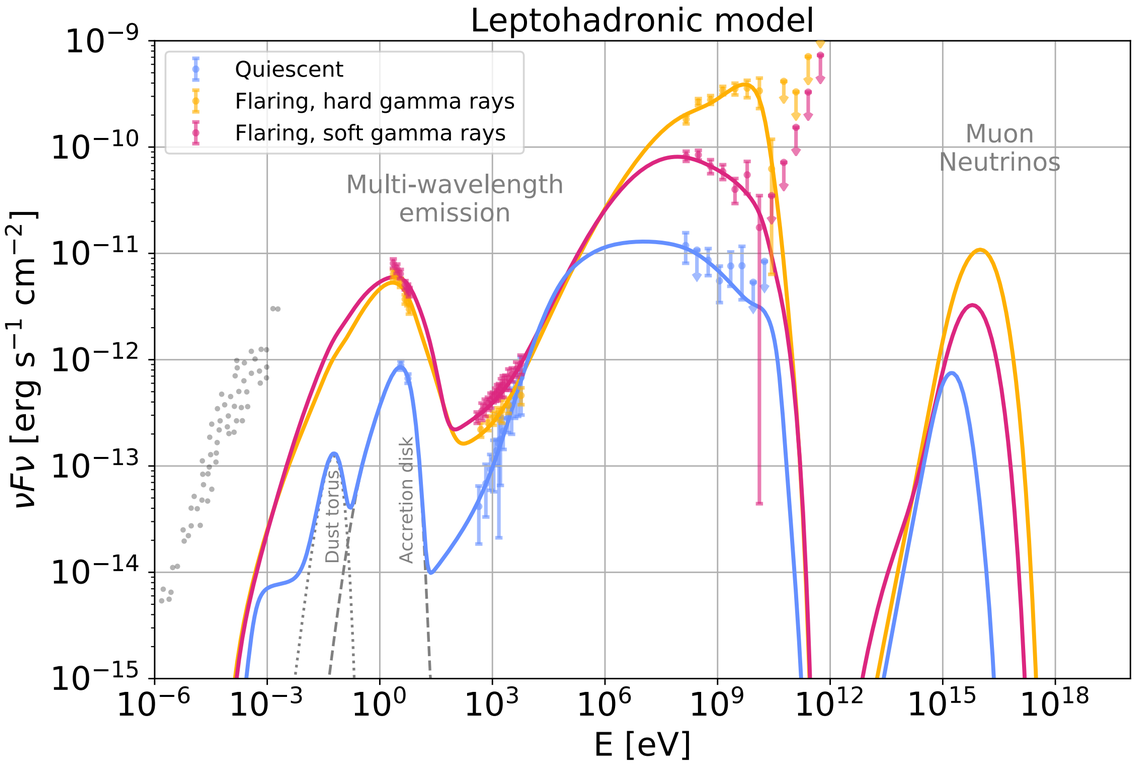
- Among the brightest FSRQs.

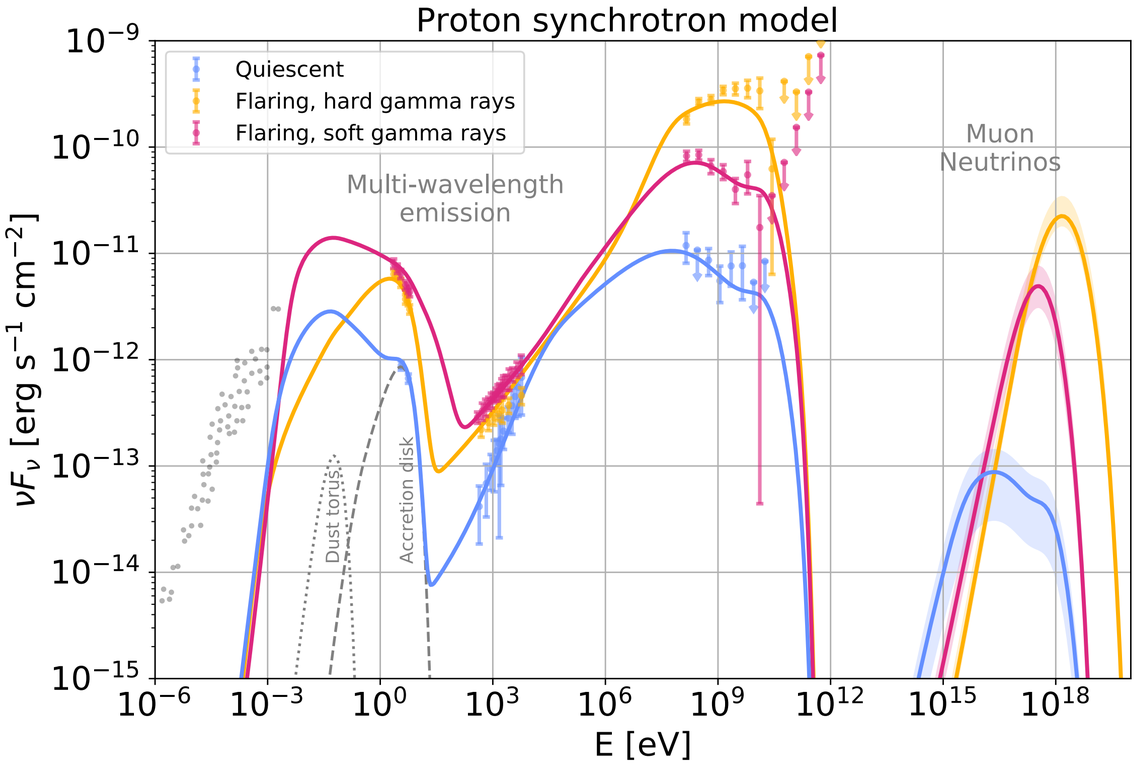


Neutrino emission during gamma-ray low-state?

MODELING OF PKS 1502+106

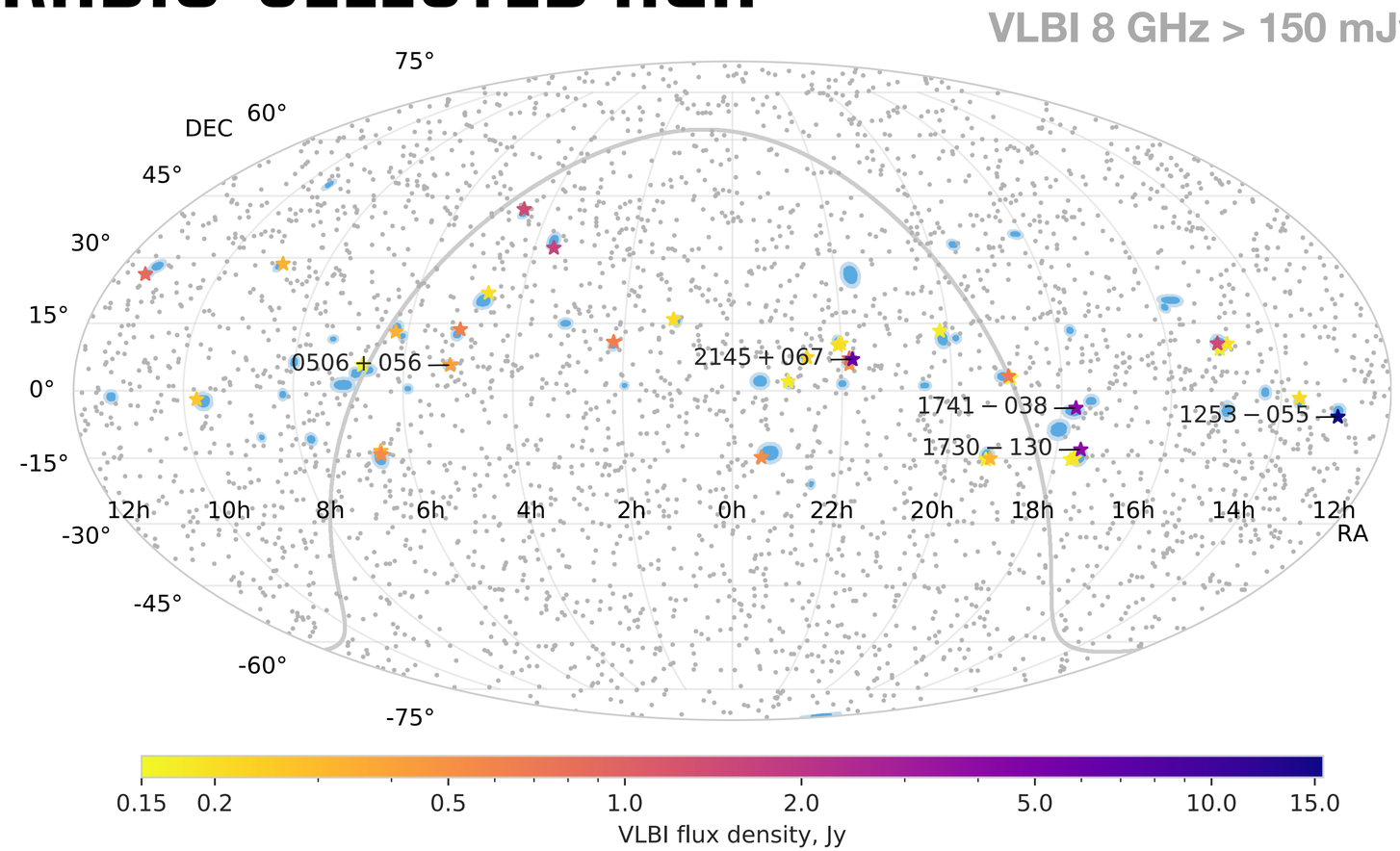
Rodrigues et al. (arXiv/2009.04026)



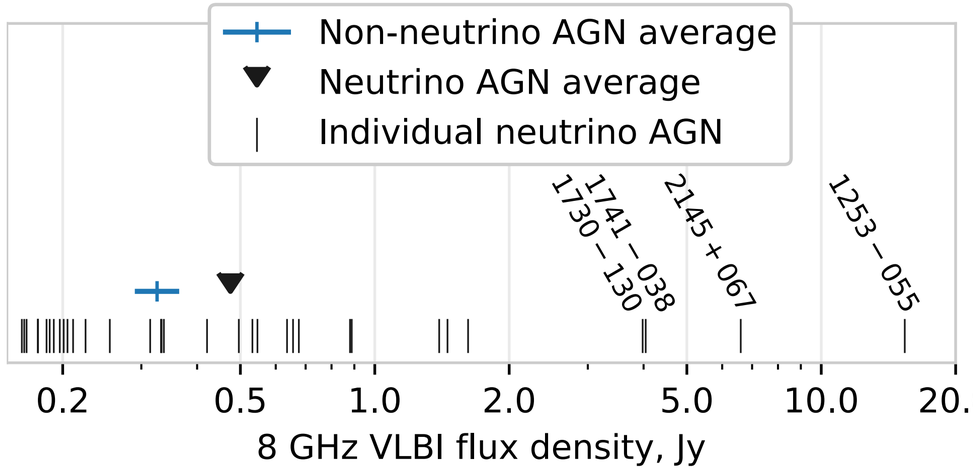


- Rodrigues et al. argue for neutrino emission during the quiescent state of the source.
- Lepto-hadronic and proton synchrotron models describe the broadband SED of the source.
- Soft X-ray spectrum suggest a hadronic contribution.

RADIO-SELECTED AGN

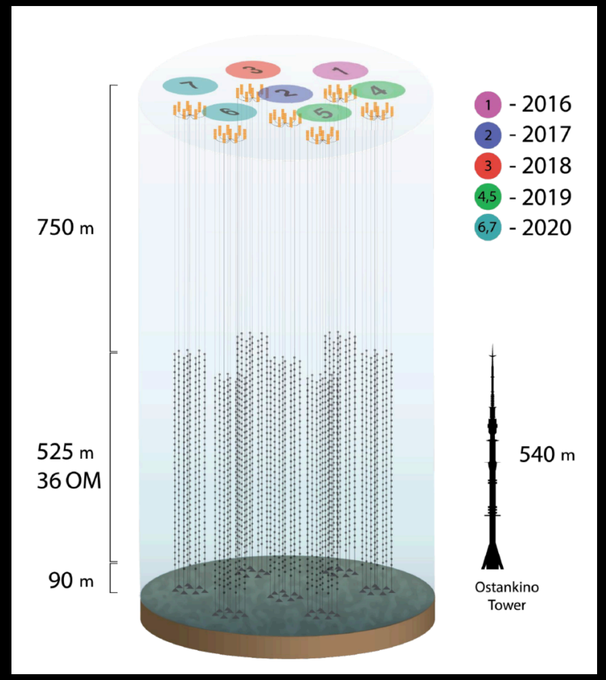


Plavin et al. (arXiv/2001.00930)



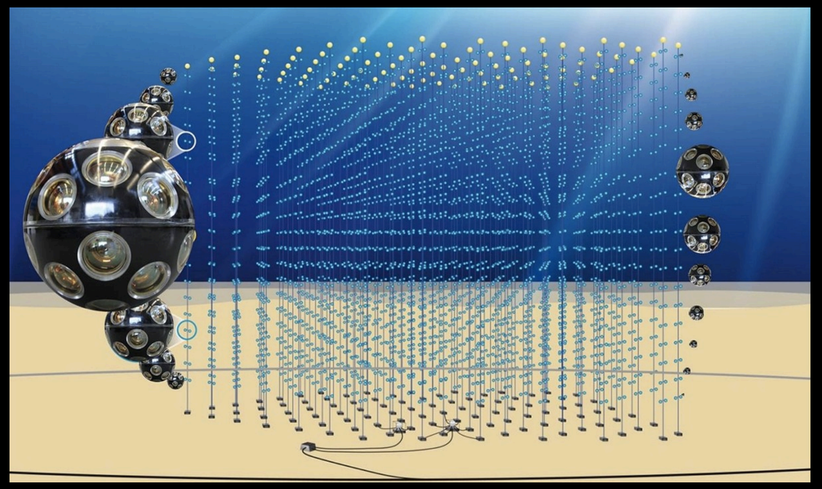
- AGN near high-energy neutrino events seem to be louder in radio.
- Correlation significance estimated at 0.2%.
- Similar studies with OVRO (Hovatta et al., arXiv/2009.10523) show no strong correlation at

MORE NEUTRINOS WITH BETTER ANGULAR RESOLUTION



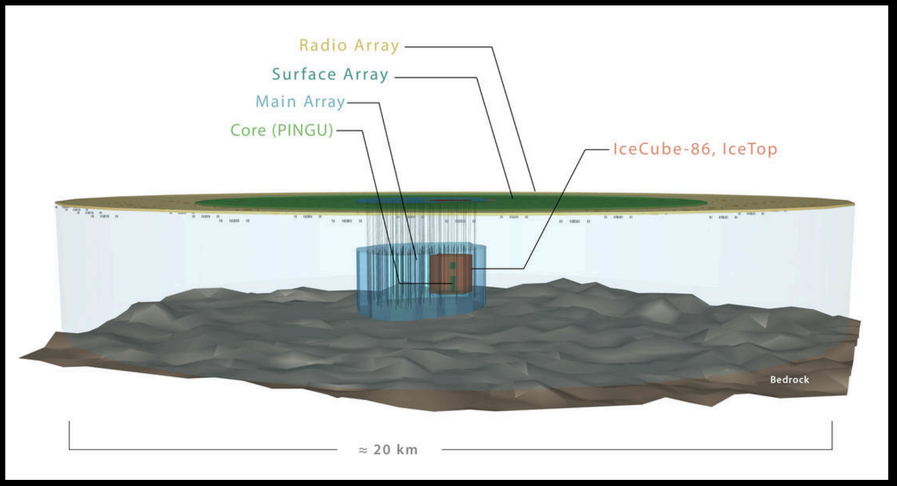
Baikal-GVD

- Target km^3-scale detector (10^4 sensors).



KM3NeT

- Target km^3-scale detector (~4k sensors in ARCA)
- 0.1° angular resolution



IceCube Gen2

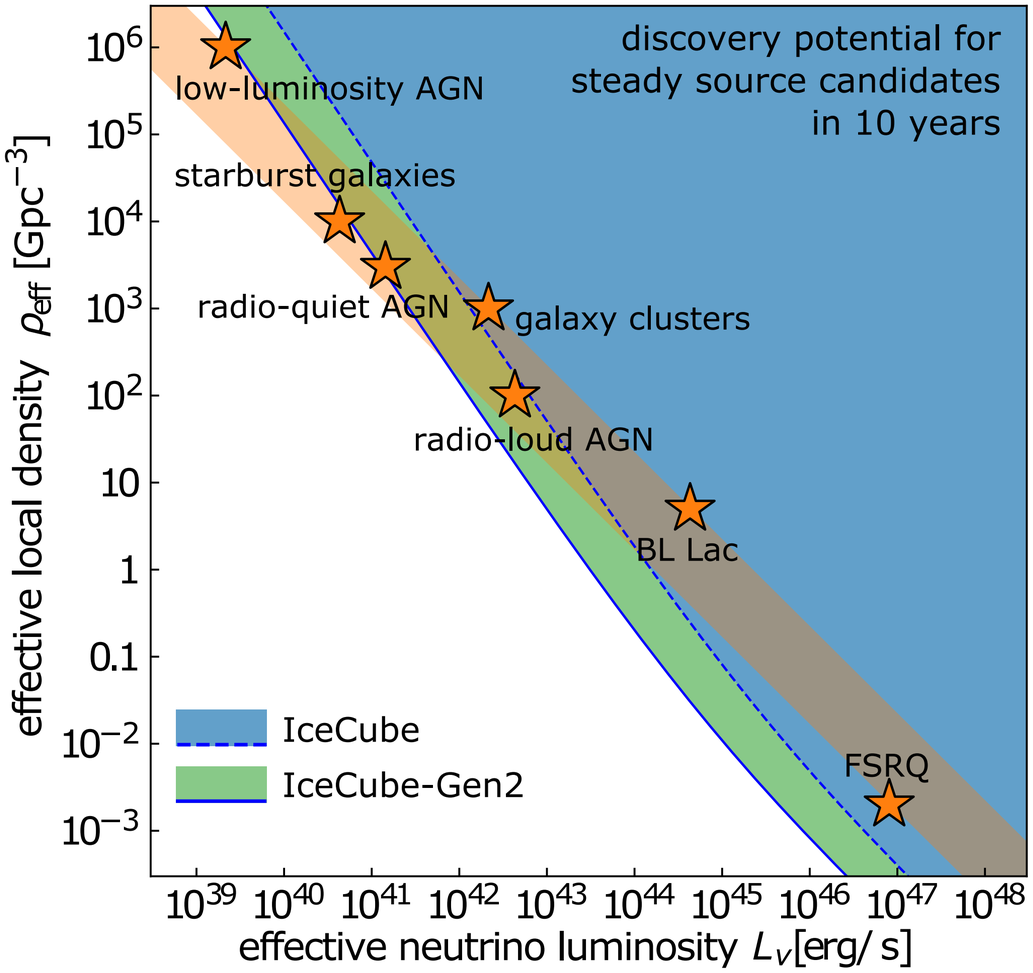
- 6.2-9.5 km^3 volume. >5x improvement in sensitivity over IceCube.
- ~0.2° angular resolution.
- Deployment to start in mid 2020s.

P-ONE
South China Sea Telescope

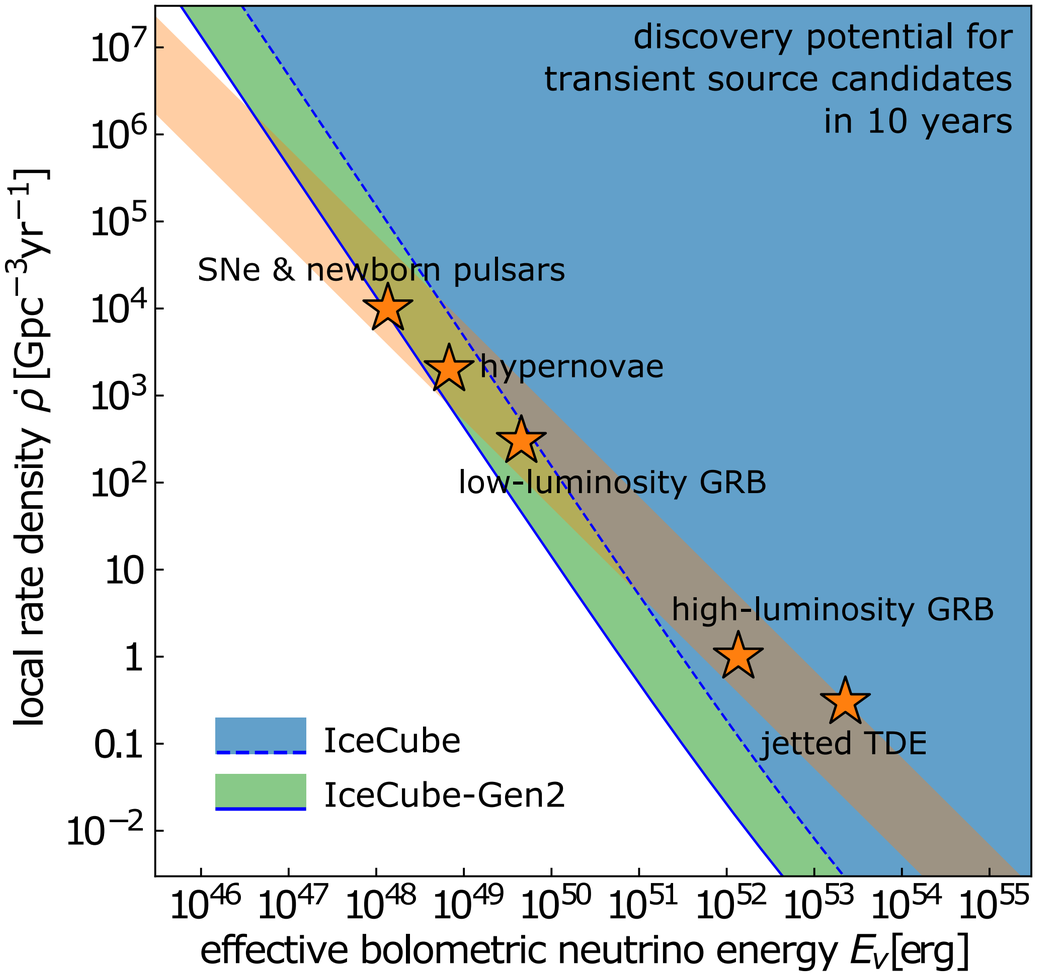
GEN-2 SENSITIVITIES

IceCube-Gen2 arXiv/2008.04323

Steady sources

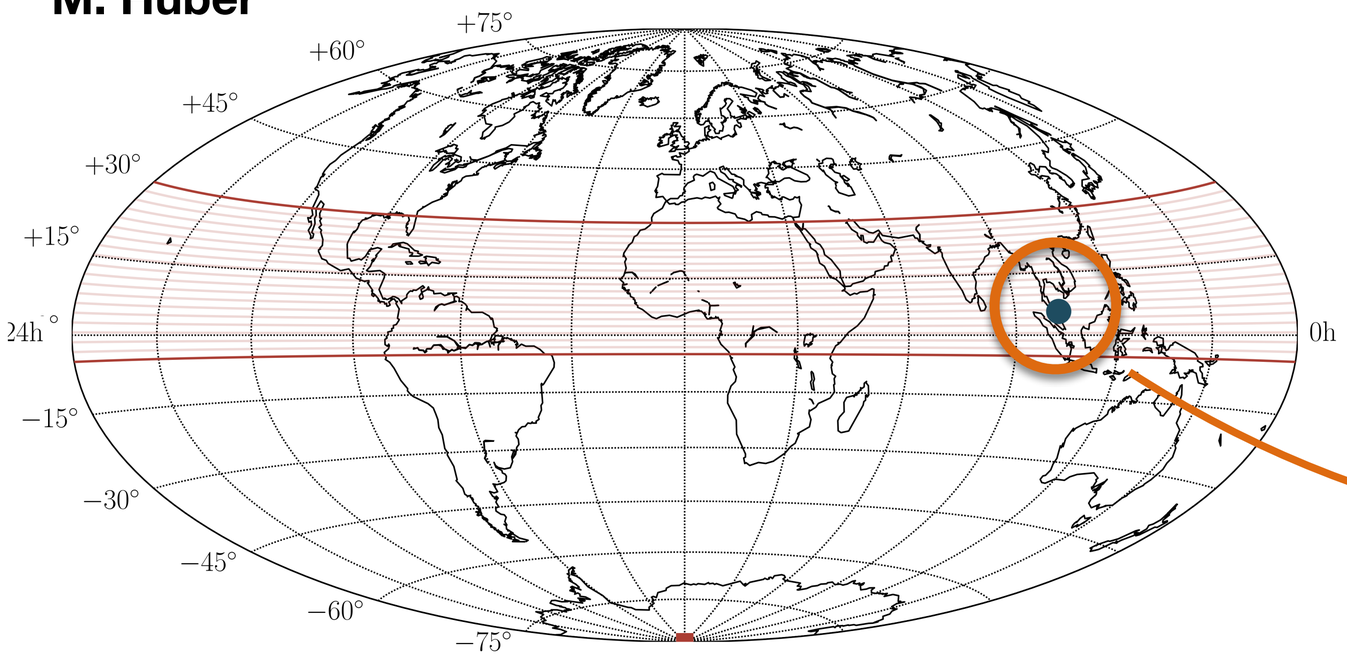


Transient sources



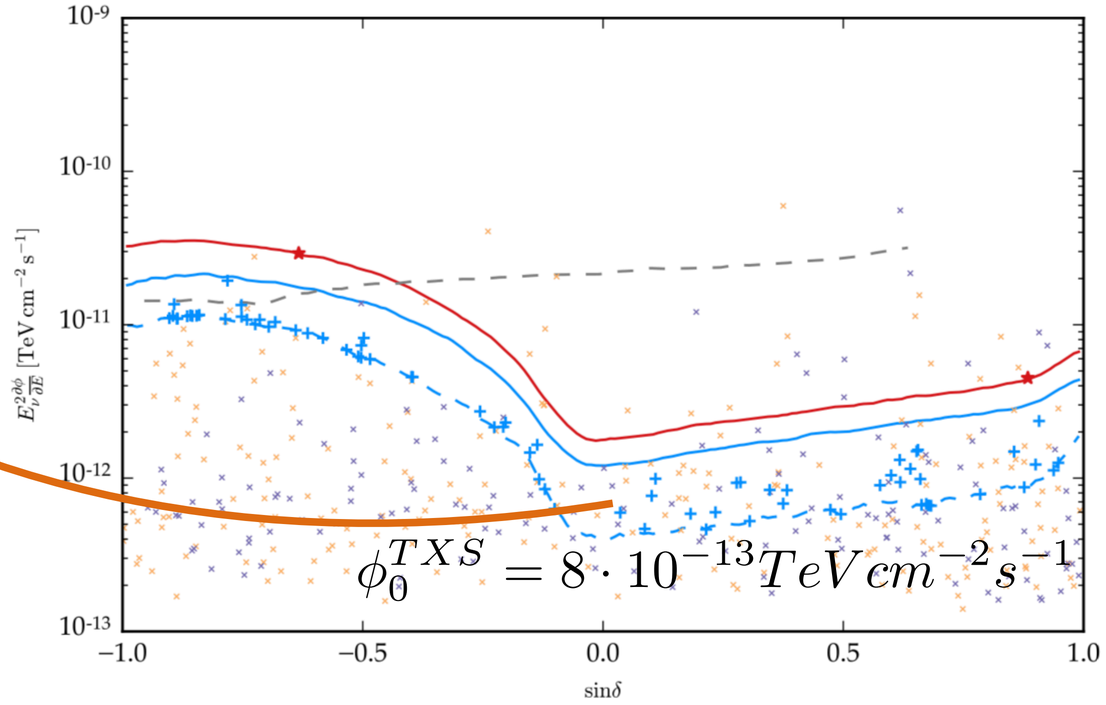
A GLOBAL NEUTRINO TELESCOPE NETWORK

M. Huber



~30% sky coverage from IceCube

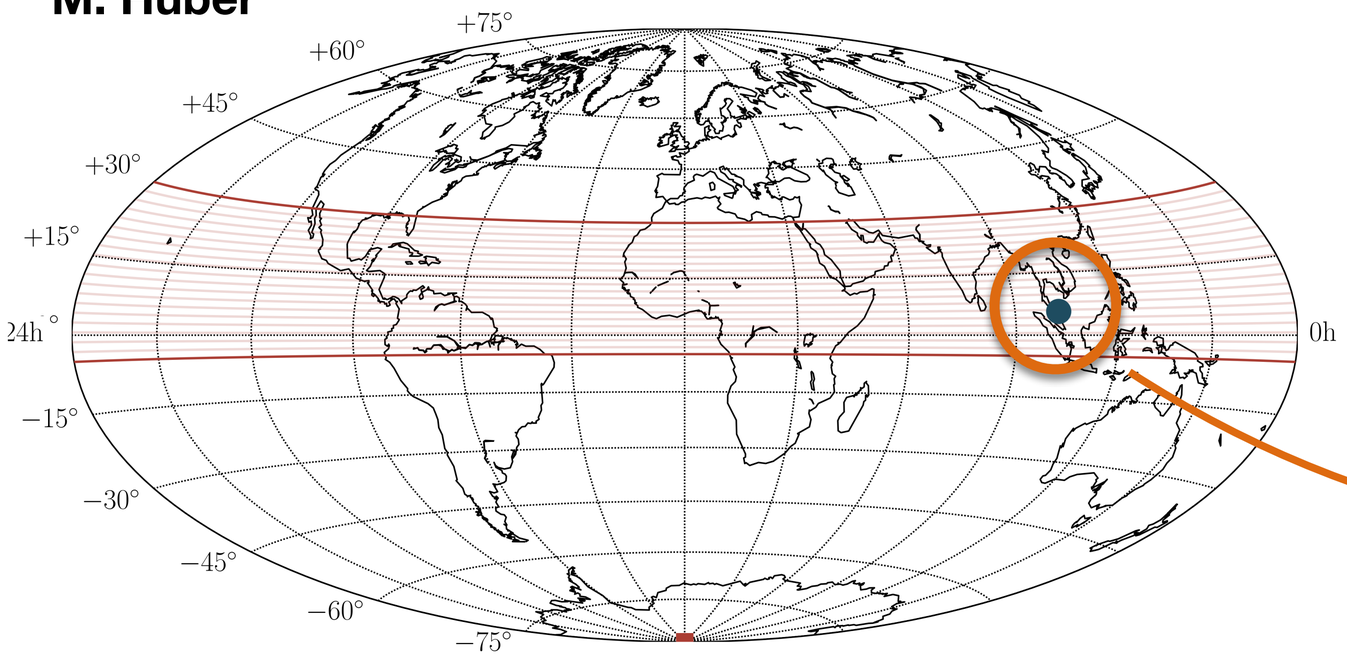
IceCube-Gen2 arXiv/2008.04323



IceCube 7year PS arXiv:1609.04981

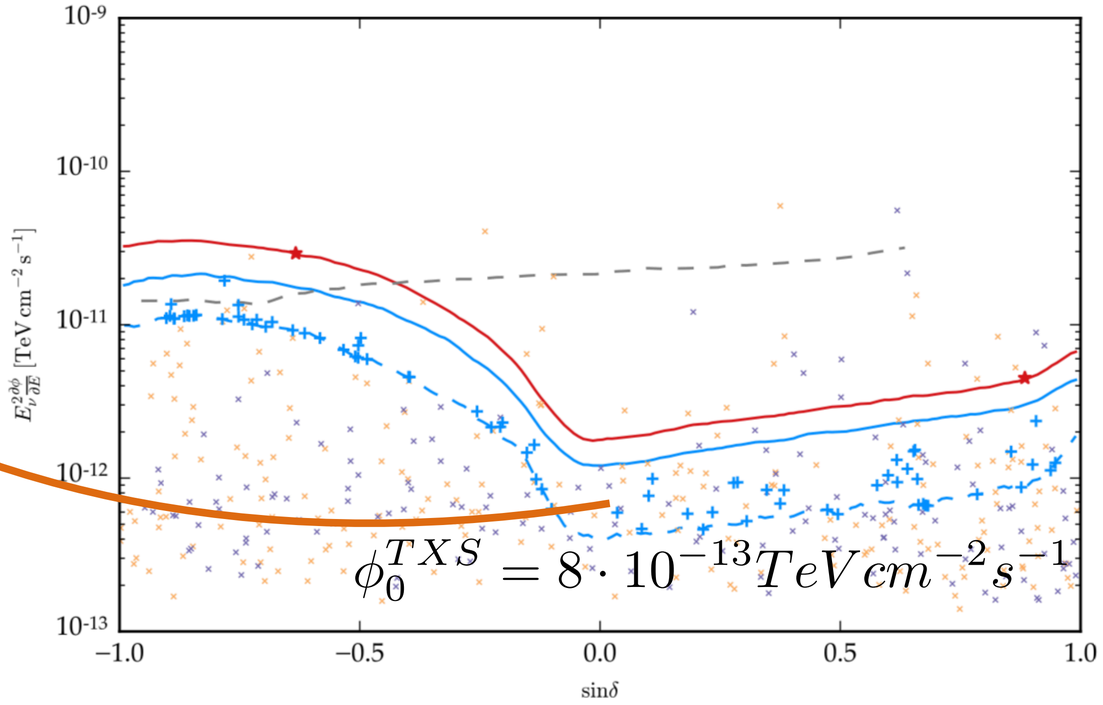
A GLOBAL NEUTRINO TELESCOPE NETWORK

M. Huber



~30% sky coverage from IceCube

IceCube-Gen2 arXiv/2008.04323

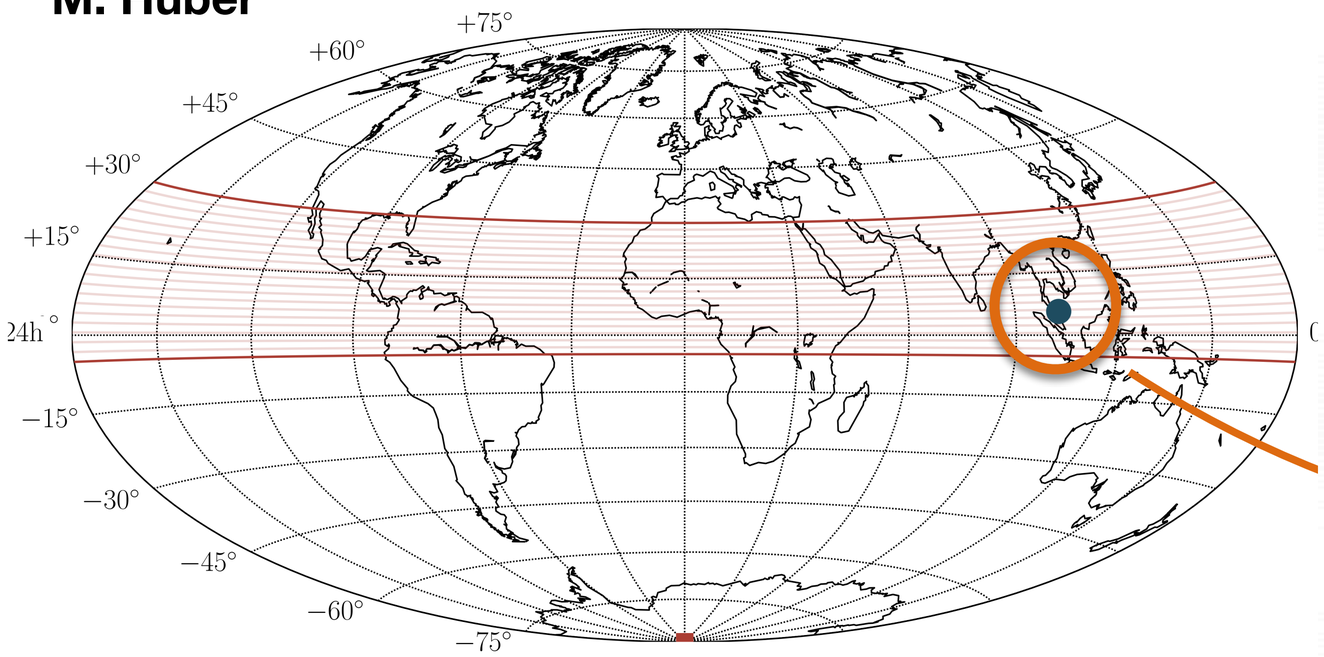


IceCube 7year PS arXiv:1609.04981

- IceCube is most sensitive near the celestial equator.
- A source similar to TXS 0506+056 may be missed if elsewhere in the sky.
- A network of neutrino telescopes is desirable to cover the entire sky with similar sensitivity.

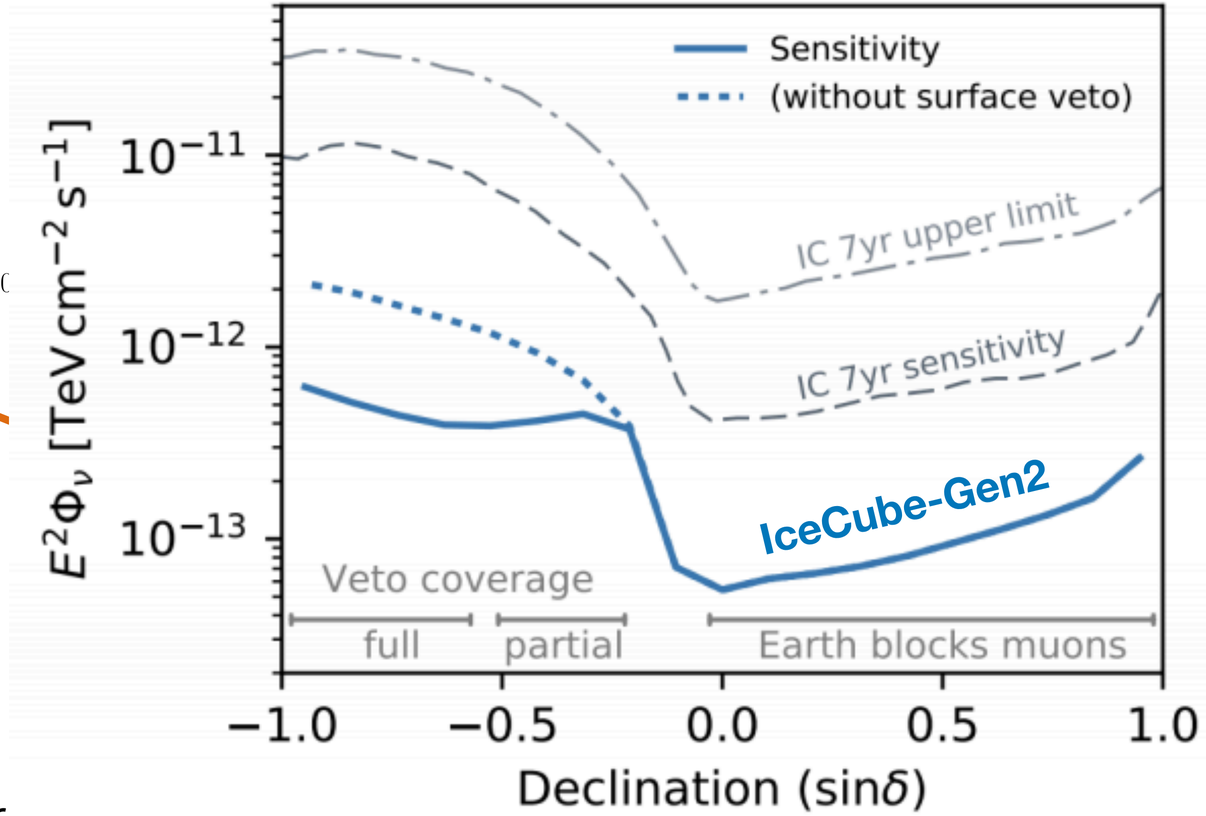
A GLOBAL NEUTRINO TELESCOPE NETWORK

M. Huber



~30% sky coverage from IceCube

IceCube-Gen2 arXiv/2008.04323

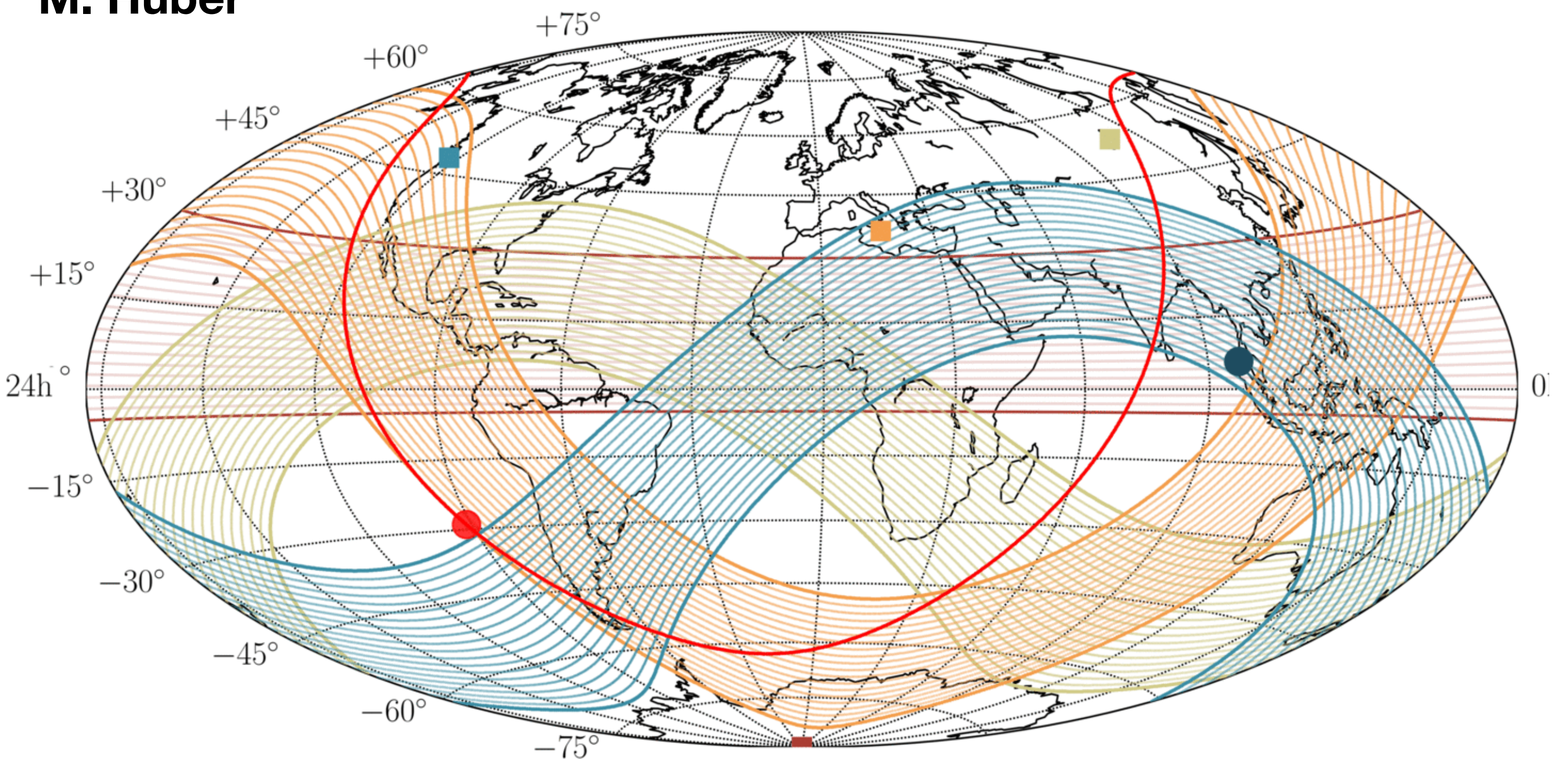


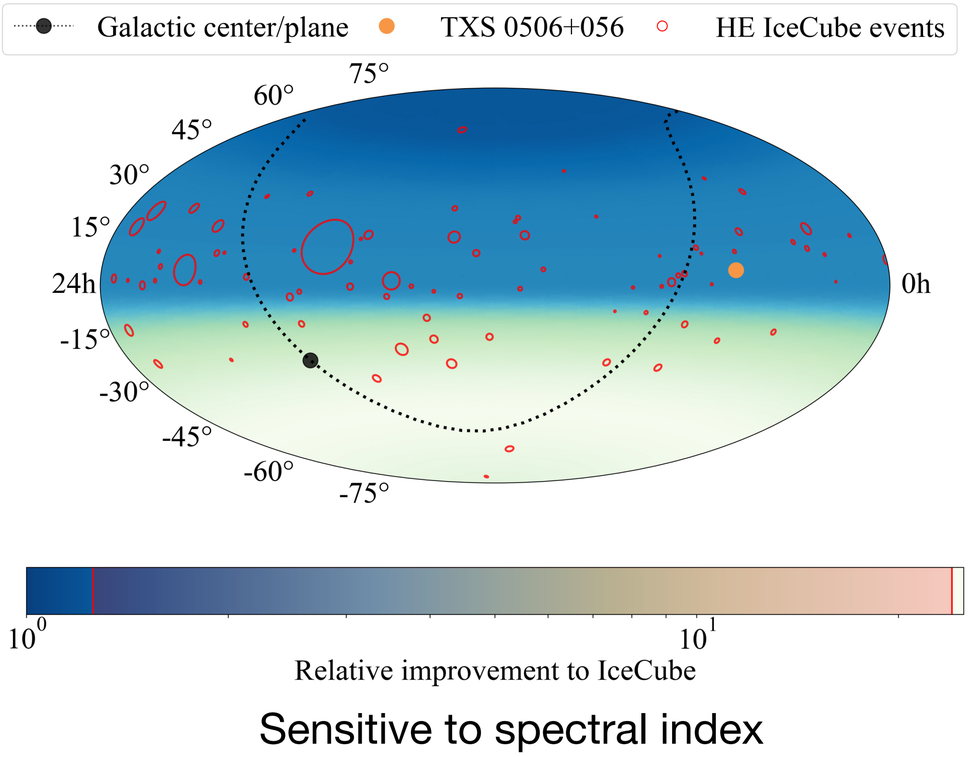
- IceCube is most sensitive near the celestial equator.
- A source similar to TXS 0506+056 may be missed if elsewhere in the sky.
- A network of neutrino telescopes is desirable to cover the entire sky with similar sensitivity.

A GLOBAL NEUTRINO TELESCOPE NETWORK

IceCube | KM3NeT, Sicily | Galactic center/plane
GVD, Russia | ONC, Canada | TXS 0506+056

M. Huber

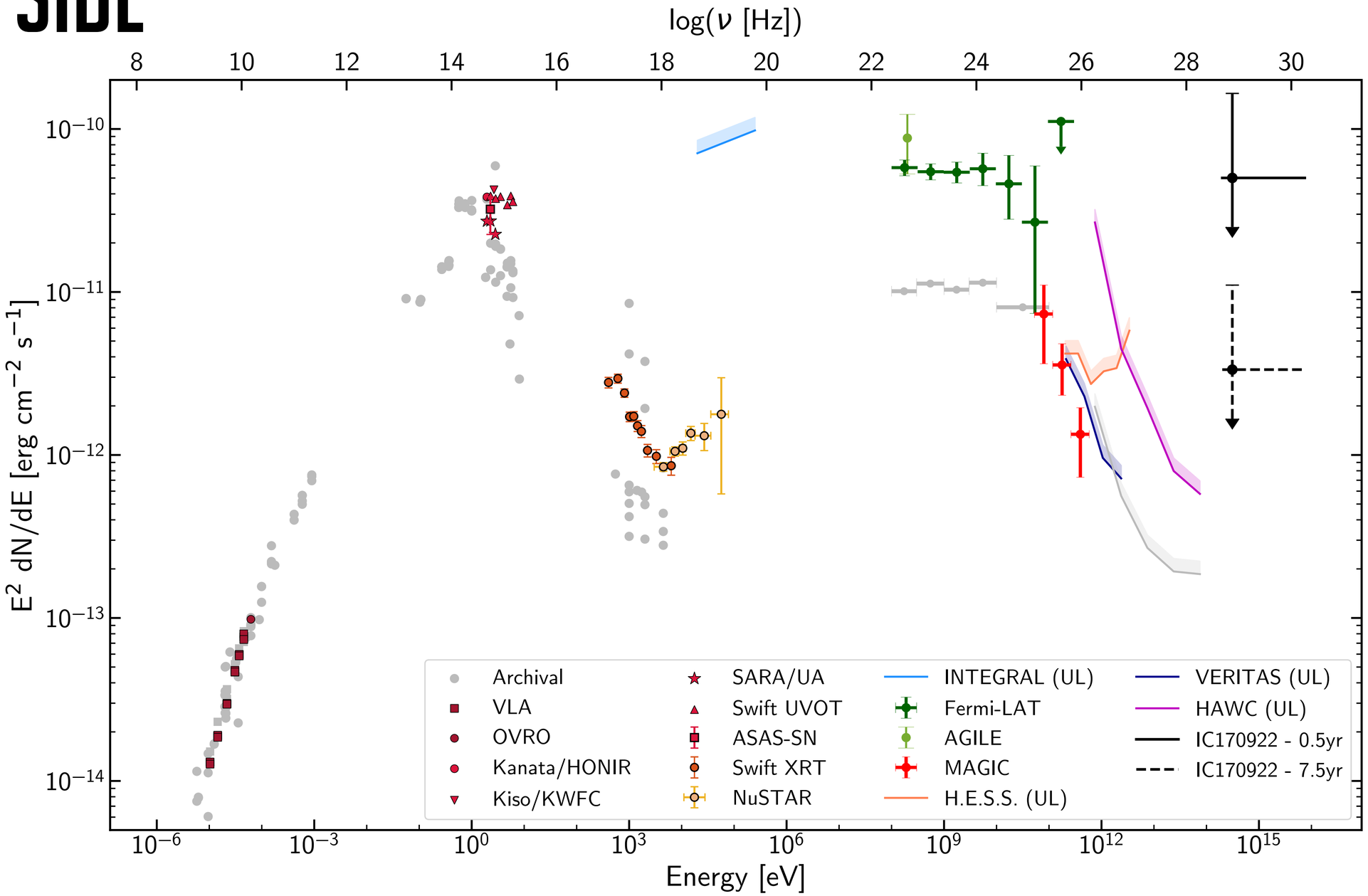




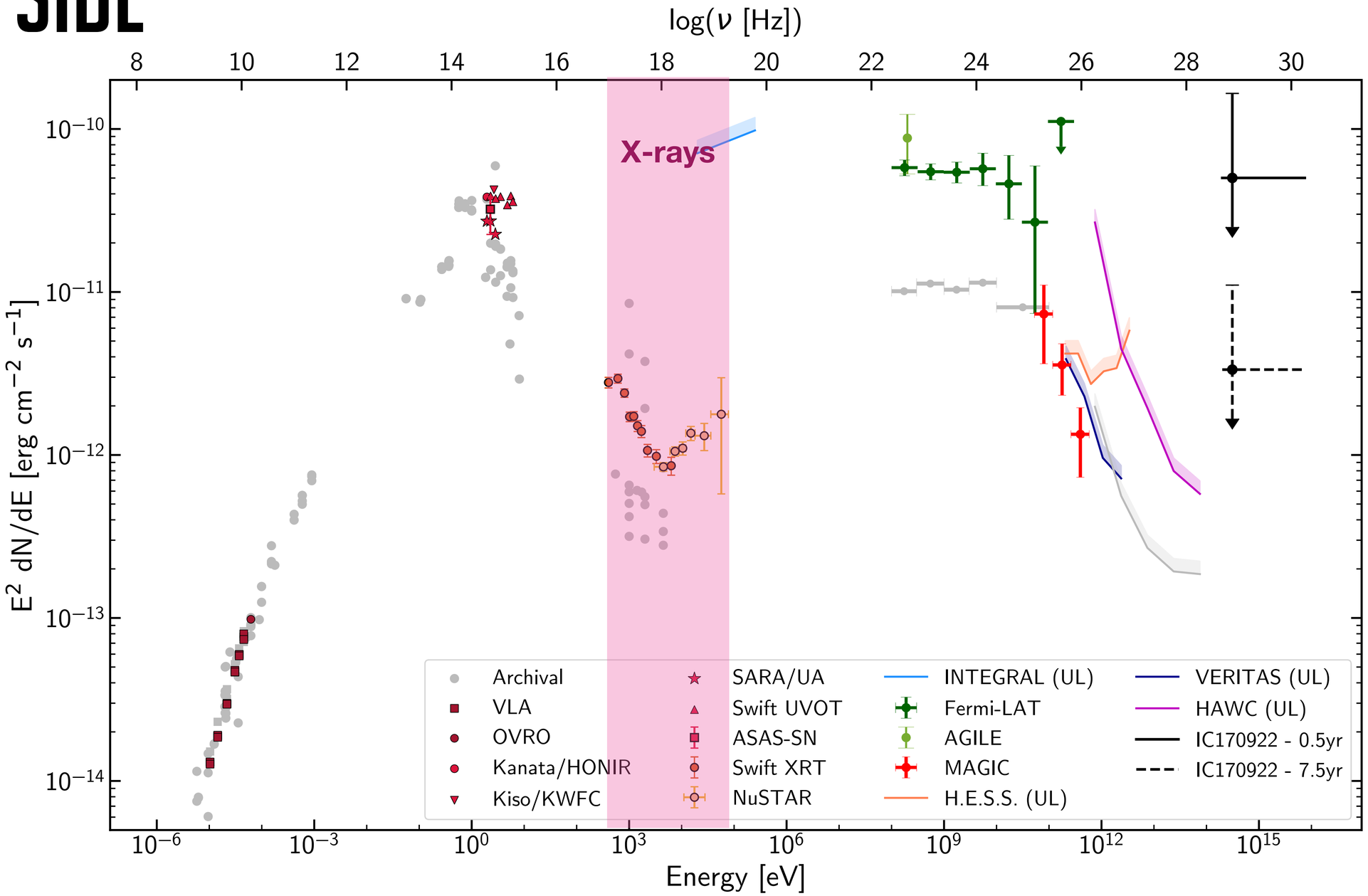
Sensitive to spectral index

- An improvement of ~25x in sensitivity could be accomplished by this network (wrt current IceCube).
- Prompt, well-reconstructed alerts from this network would enable sensitive **EM follow-ups**.

THE EM SIDE


log(ν [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
IC170922 - 0.5yr
IC170922 - 7.5yr

THE EM SIDE


log(ν [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
X-rays
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
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HAWC (UL)
IC170922 - 0.5yr
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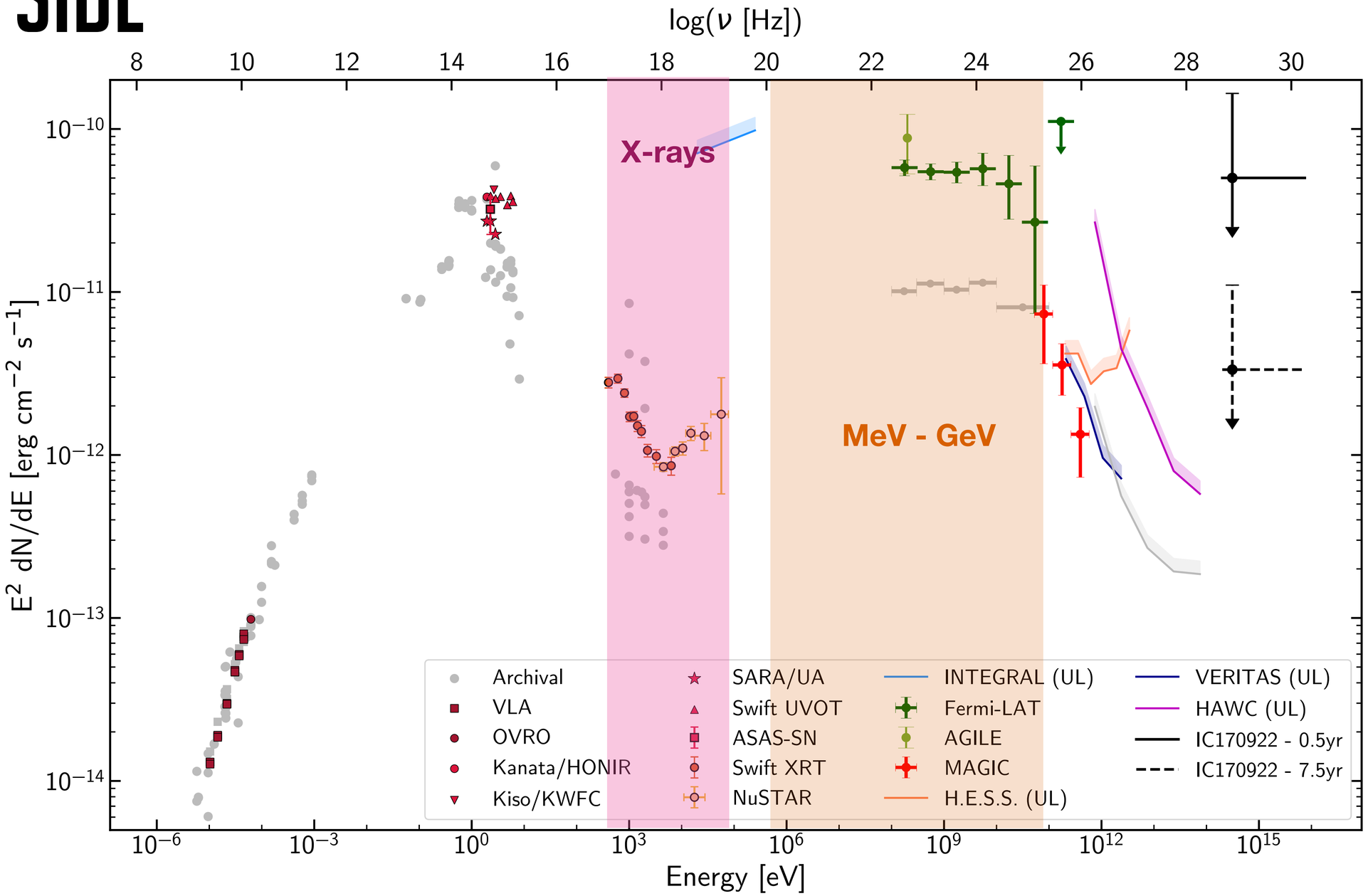
THE EM SIDE


log(ν [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
X-rays
MeV - GeV
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
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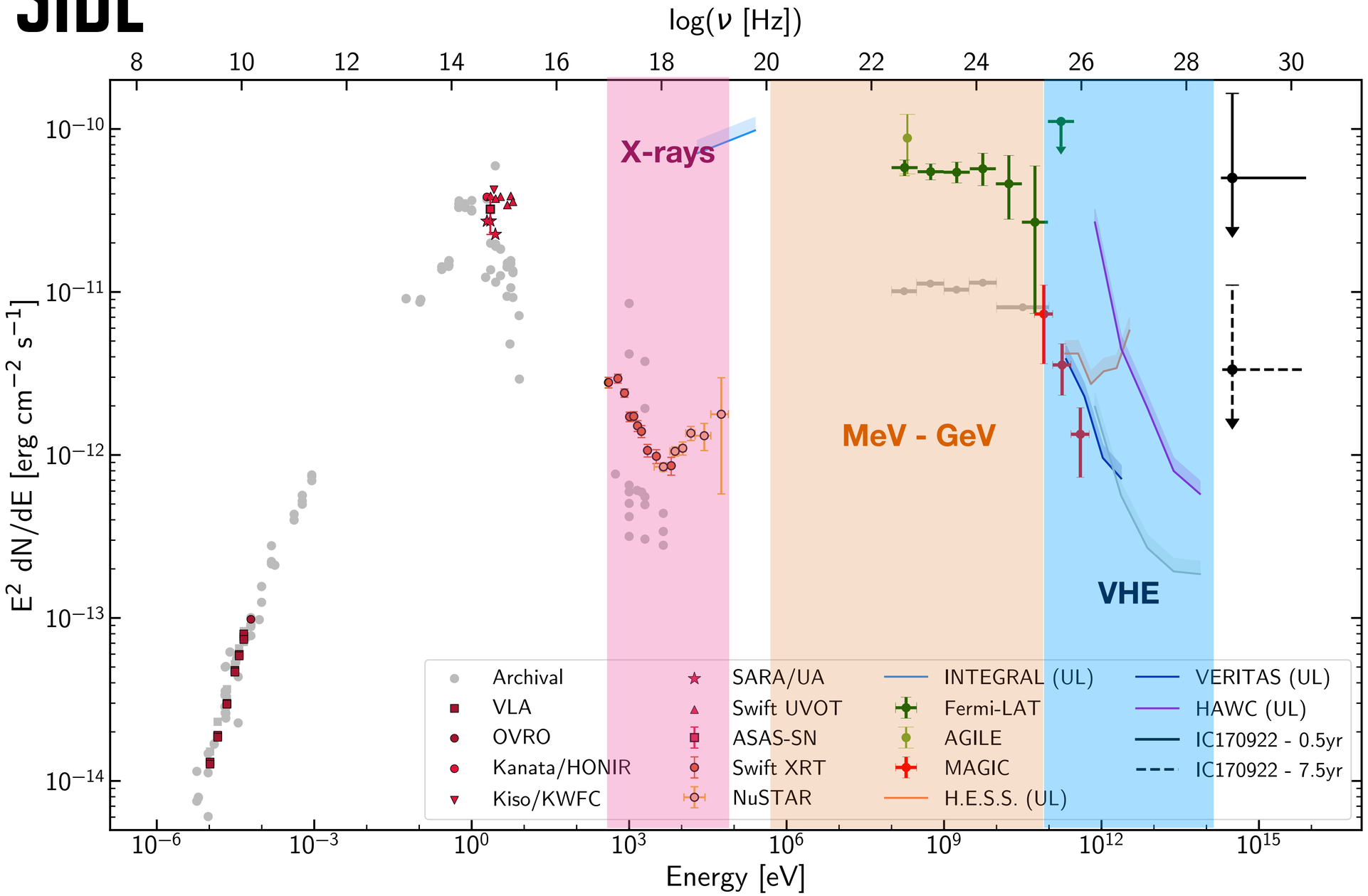
THE EM SIDE


log(ν [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
X-rays
MeV - GeV
VHE
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
Energy [eV]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Archival
VLA
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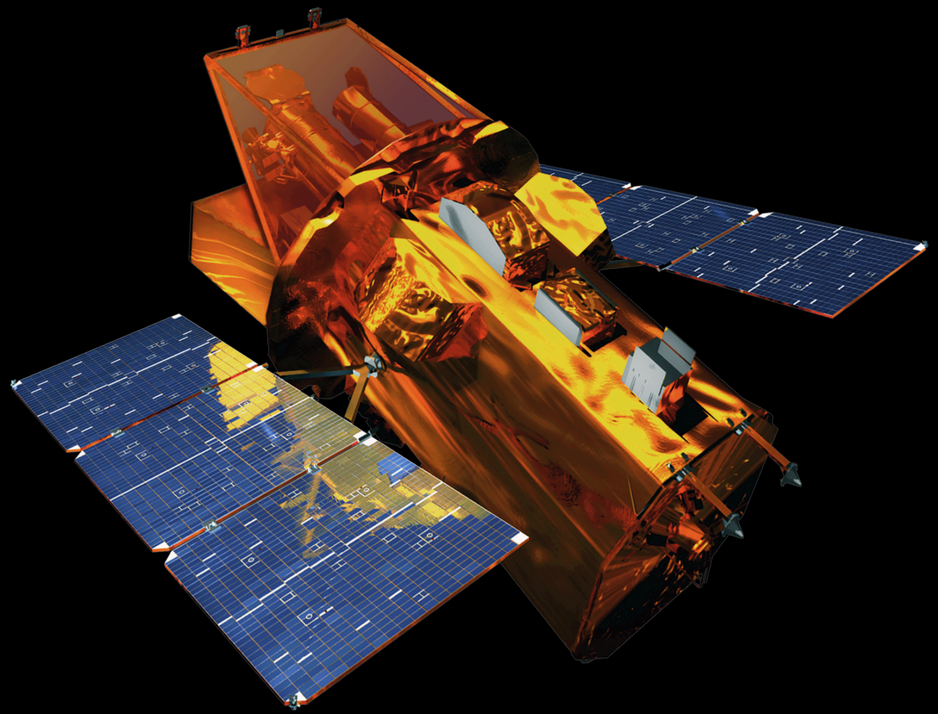
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
IC170922 - 0.5yr
IC170922 - 7.5yr

X-RAY COVERAGE

Neil Gehrels *Swift* Observatory



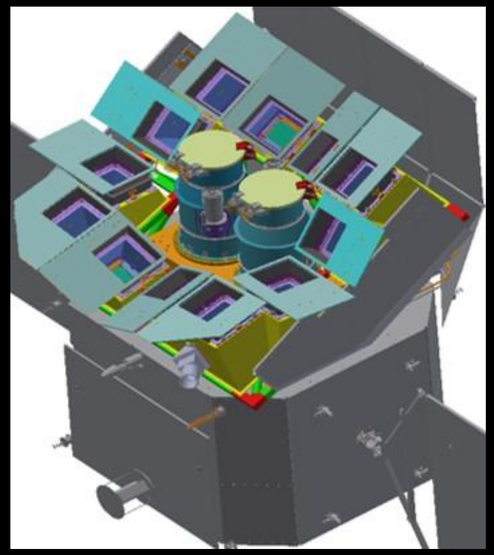
XRT sensitivity in the 0.3-10 keV
Fast response, low overhead.
110 cm^2
~10^{-13} erg/cm2/s in ~2 ks
~0.4 deg FoV
Launched in 2004.

SVOM (China-France)

Rapid follow-ups of GRBs
Launch date of Mid 2023
0.2-10 keV
“Lobster eye” optics with
1 deg FoV

Jul 2020: NJU-HKU
No.1 lobster-eye
demonstrator launched.

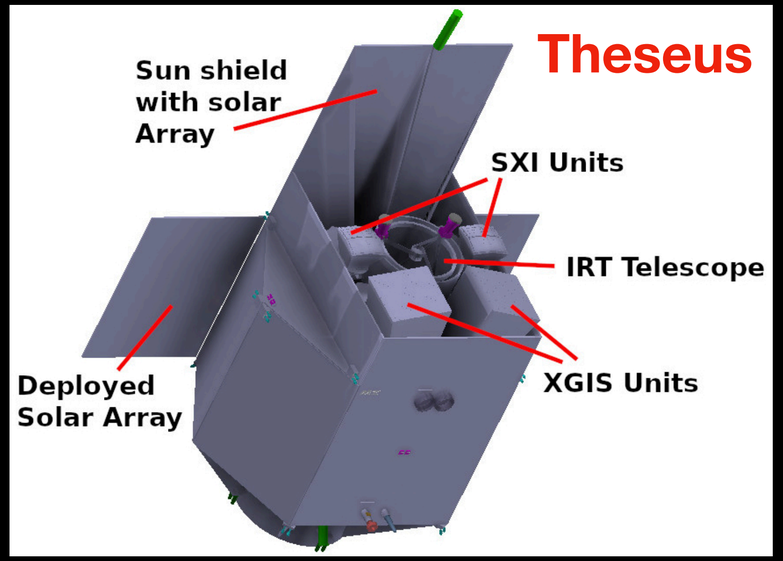
Einstein Probe (China-ESA)



Mid to late 2023 launch

lobster-eye MPO + CMOS	Wolter-1 type + CCD
FoV: 3600 sq deg (1.1 sr)	FoV: 38’
band: 0.5 – 5 keV soft X-ray	band: 0.3-10keV
eff. area: ~3 cm^2 @1keV	eff. area: 2x 300cm^2 @1keV
FWHM: ~ 5’, positioning <1’	angular FWHM: 30”
Sensitivity: 10-100 x increase	positioning accuracy: <10”

X-RAY COVERAGE



Soft X-ray Imager (SXI): 0.3 - 5 keV
Total FoV of ~0.5 sr with a localization accuracy of <2’

XGIS: 2 keV - 10 MeV with FoV >2 sr with < 15’ GRB localization

Not selected as of 2022.

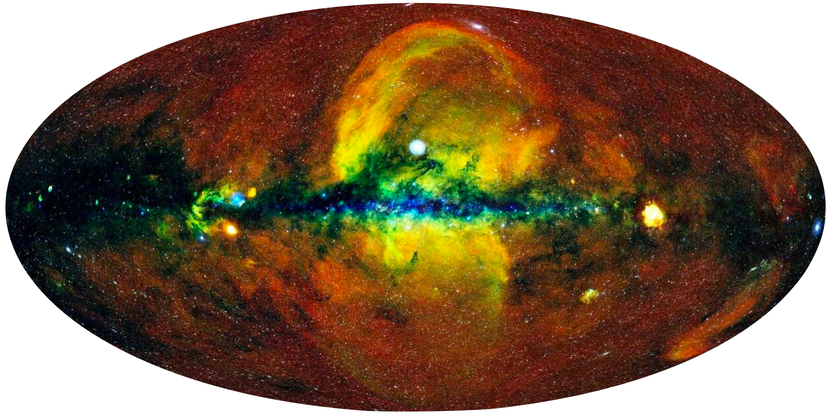
STAR-X (NASA)

PI W. Zhang (NASA)

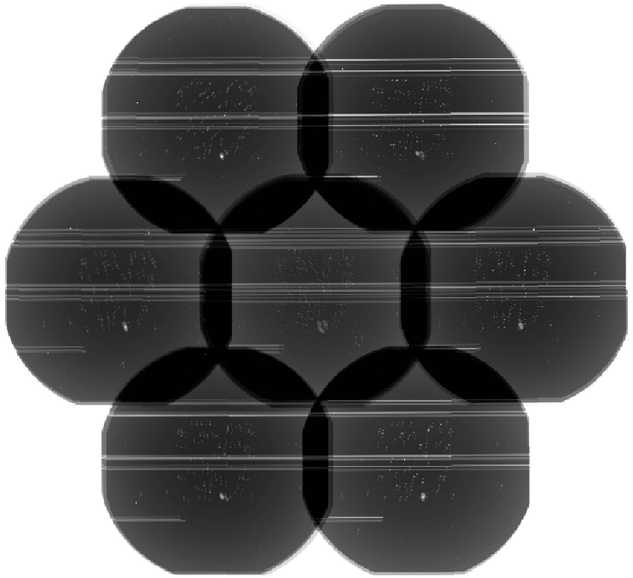
Selected (with UVEX) for a MIDEX Concept Study
x7 FoV of Swift XRT
x16 effective area

	X-ray Telescope (XRT)	UV Telescope (UVT)
PSF	2.5” on-axis 10” 0.5° off-axis	4.5”
FOV	1 deg^2	1 deg^2
Band width	0.5 – 5 keV	160 – 350 nm
Effective Areas	@1keV: 1,800 cm^2 on-axis 900 cm^2 0.5° off-axis	7 different filters: 25 - 55 cm^2
TOO Response	~60 minutes	
Field of Regard	80% of the sky every 90 minutes	

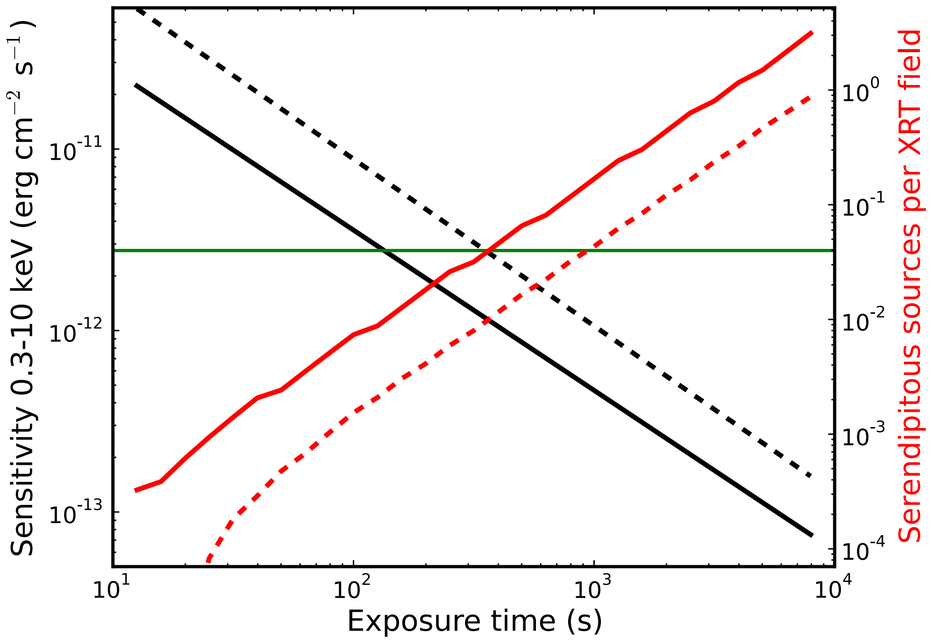
ASSOCIATION PROBABILITY A CRITICAL FACTOR



- Pointed follow-ups require a good reference catalog to compare against **(e.g eROSITA)**. We don't know (yet!) what exactly we're looking for!
- Sources are transient or highly variable, hampering strong predictions. An emerging pattern is necessary.
- **Calculation of probabilities is a critical factor in correlation claims.**



Swift tiling of neutrino position

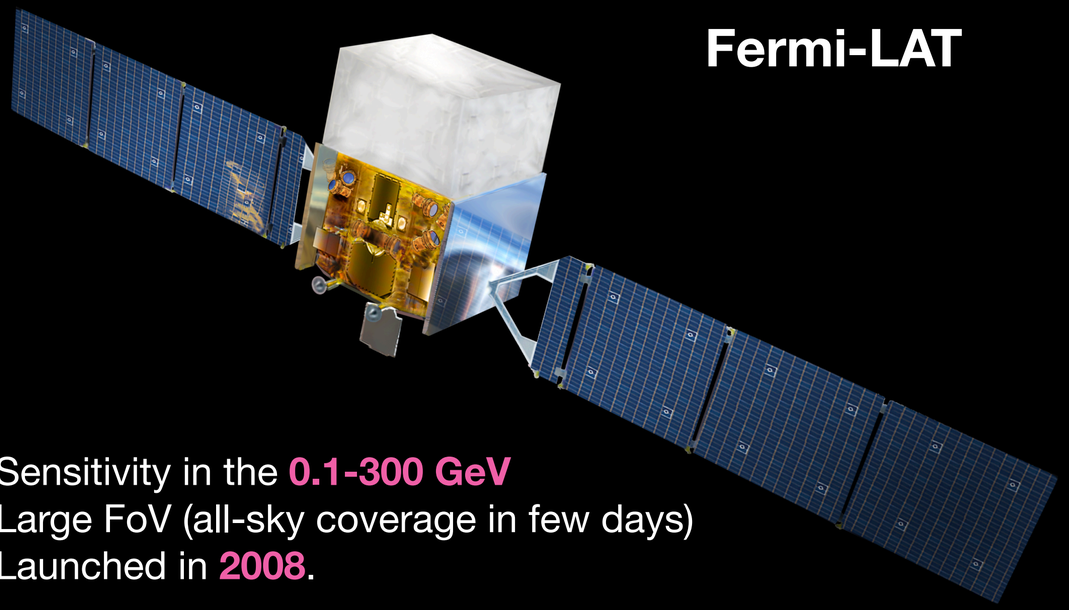


Swift follow-up of neutrino events

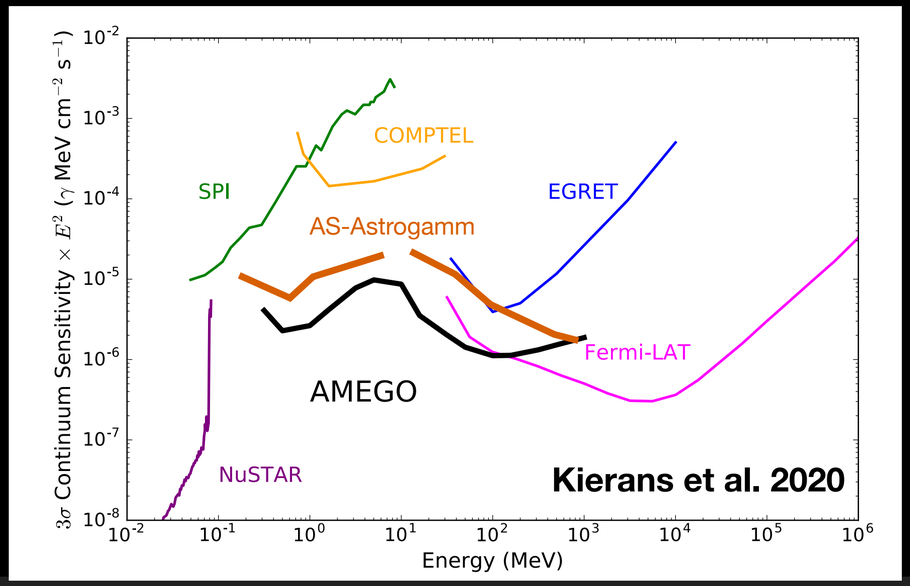
Evans et al.
https://arxiv.org/abs/1501.04435

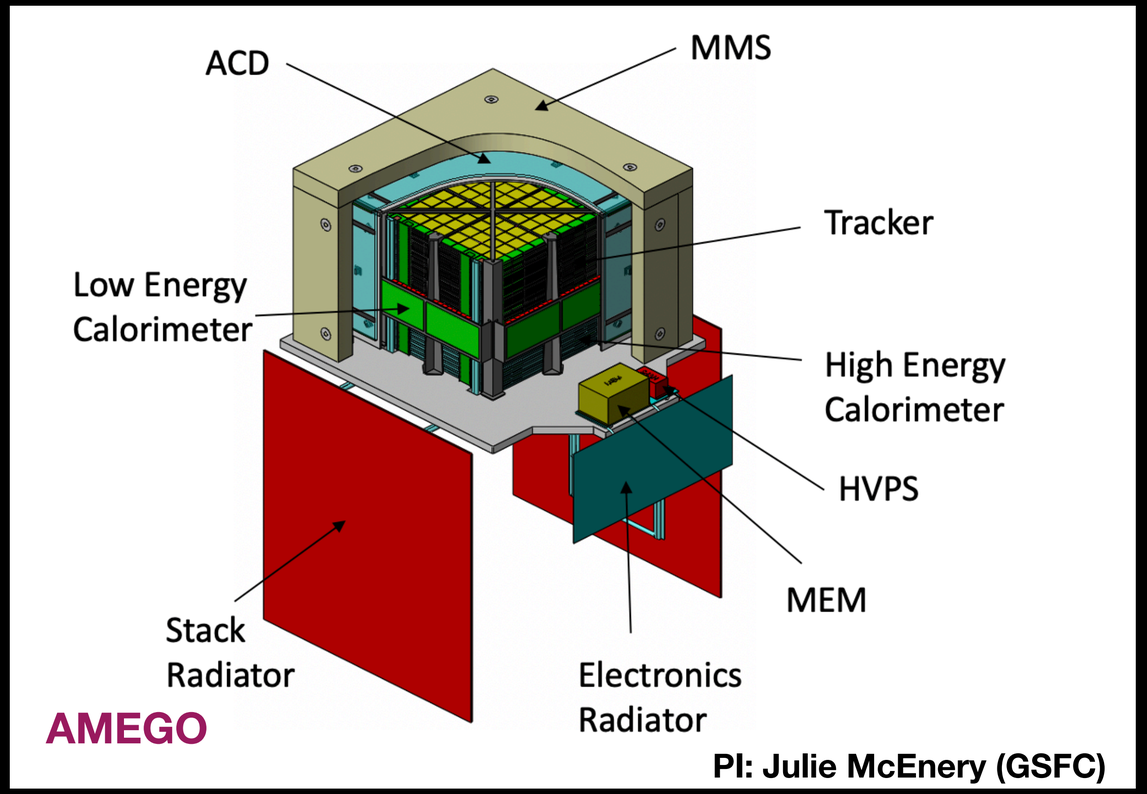
MEV-GEV COVERAGE

Fermi-LAT



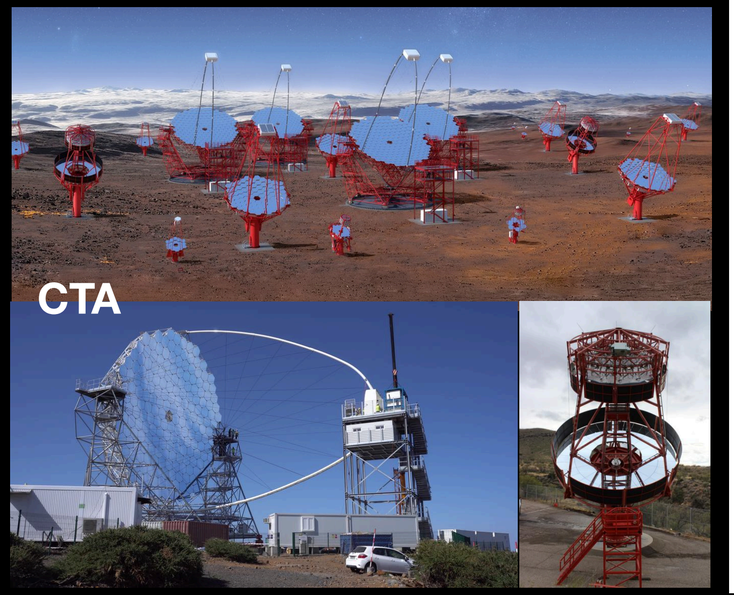
Sensitivity in the **0.1-300 GeV**
Large FoV (all-sky coverage in few days)
Launched in **2008**.

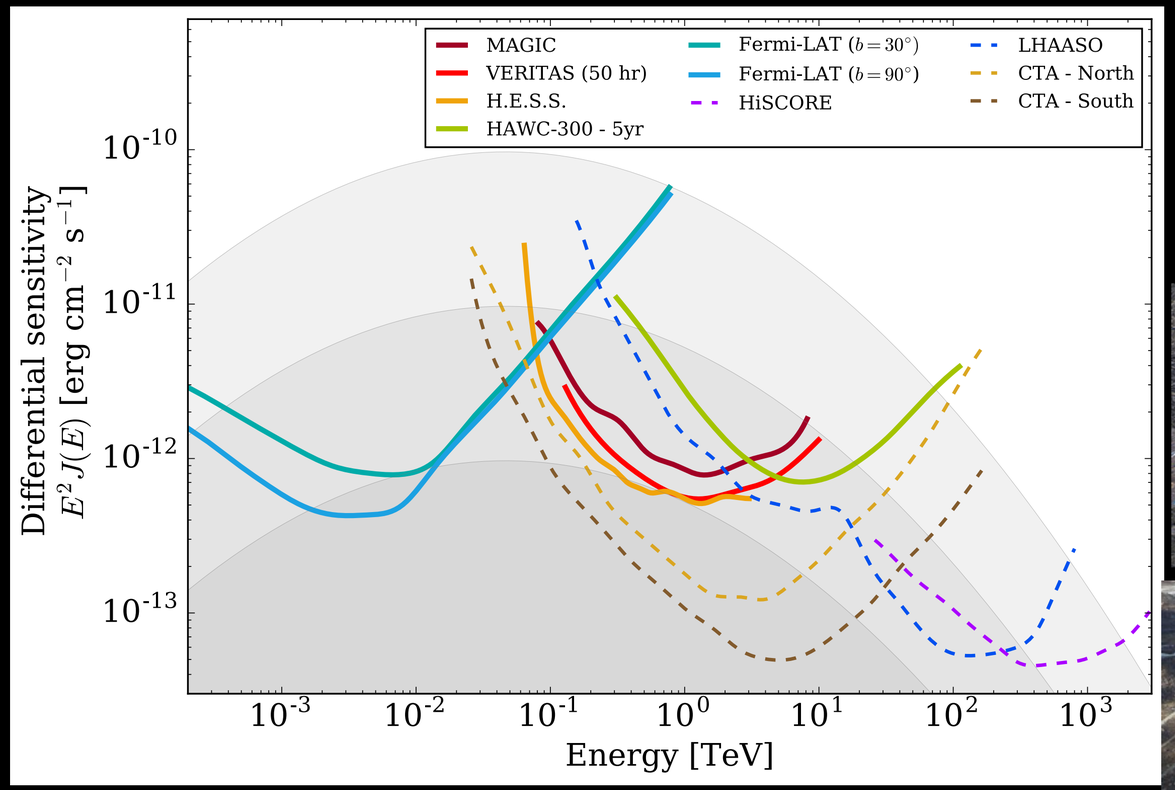


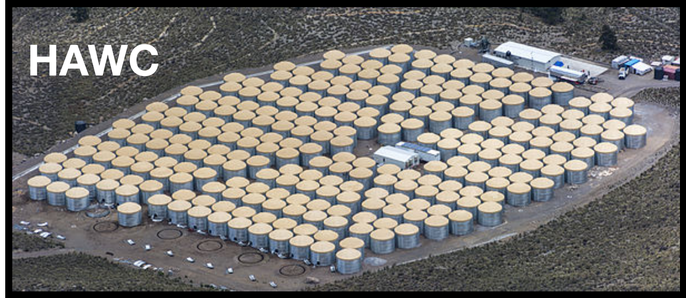


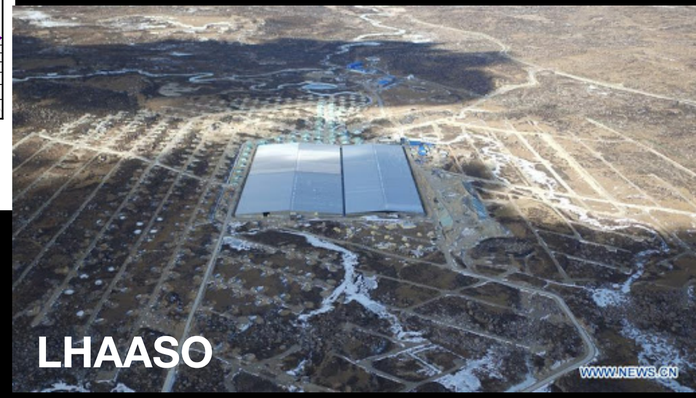
- AMEGO angular resolution: 3° (1 MeV), 10° (10 MeV)
- AMEGO prototype (**ComPair**) for balloon flight.
- European MeV effort concentrated on **All-Sky-Astrogamm** mission study.
- Continued support for **Fermi.**

VHE COVERAGE









SWGO in the Southern Hemisphere

- CTA to provide a x10 improvement in sensivity in the VHE band (>50 GeV). Prototypes telescopes already detecting sources, observations to start in ~2025.
- Neutrino follow-ups and strong AGN science program for CTA.
- Air shower arrays (HAWC, LHAASO, proposed SWGO) provide large FoV coverage with high duty cycle although with a higher threshold.

TAKE-AWAY POINTS FOR REALTIME CORRELATIONS WITH AGN

- Increase the number of neutrino events >100 TeV (high astrophysical purity)
- Improve the angular resolution (correlation probability goes with PSF^2)
- As neutrino telescopes are 4π instruments, you need wide-field, continuous, broad-band, sensitive coverage across the AGN SED.
  - **New instruments** where sensitivity is currently lacking (soft X-rays to MeV range, improved sensitivity in the VHE range).
  - **Continued operation** of instruments with no obvious substitute (e.g. Fermi)

CURRENT COMMUNICATION INFRASTRUCTURE

GODDARD SPACE FLIGHT CENTER

GCN Help/FAQ
GCN What's New
NASA Homepage

SEARCH NASA

GCN HOME | ABOUT GCN | BURST/TRANS INFORMATION | MEMBERSHIP | ARCHIVES | SEARCH GCN FOR BURSTS

GCN: The Gamma-ray Coordinates Network (TAN: Transient Astronomy Network)

14 Feb 2022: There was trouble in printing and processing of Circular #31590.

27 Dec 2021: Earlier today an acciedent in processing caused some old email Notices to be resent. There were 3 intervals of old Notices from short windows of time: Oct 23, Nov 01, and Dec 04, 2021. They were correct Notices of their time and content, but just retransmitted (duration of ~1 hour between 06:40 to 07:40 UT today). This occurred for only those recpients that use the email method. We apologize for the confusion that occurred.

03 Nov 2021: The Time-domain Astronomy Coordination Hub (TACH) project is pleased to announce a new community tool to access the archive of GCN Notices and Circulars. The GCN Viewer ingests new notices and circulars in real time, and associates events detected by multiple facilities, providing useful categorization and searchability. This first public release of the GCN Viewer provides this functionality, and new features will be added with forthcoming releases. The new TACH archive of the GCN Notices & Circulars is accesible through the GCN Viewer at https://heasarc.gsfc.nasa.gov/tachgcn

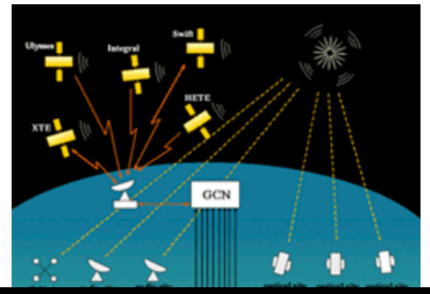
Posted 23 Mar 2020 (last updated 18 Oct 20):
Due to the policies and constraints during the CoronaVirus pandemic, my response to your requests and questions may not be as fast as normal.
Example: changes to your site_configuration may take up to 7 days (instead of the usual 2-4 days).
Being at home teleworking, requires making the site_config file change a remote operation instead of the normal on-site operation. Which is doable, but I try to keep that method to a minimum. I will wait longer to do the file change or I will use a weekly 4-hr pass to do work on-site.

The GCN system distributes:

1. **Locations of GRBs and other Transients (the Notices)** detected by spacecraft (most in real-time while the burst is still bursting and others are that delayed due to telemetry down-link delays).
2. **Reports of follow-up observations (the Circulars)** made by ground-based and space-based optical, radio, X-ray, TeV, and other particle observers.

These two functions provide a one-stop shopping network for follow-up sites and GRB and transient researchers.

The GCN system can be explored using the links above and below.



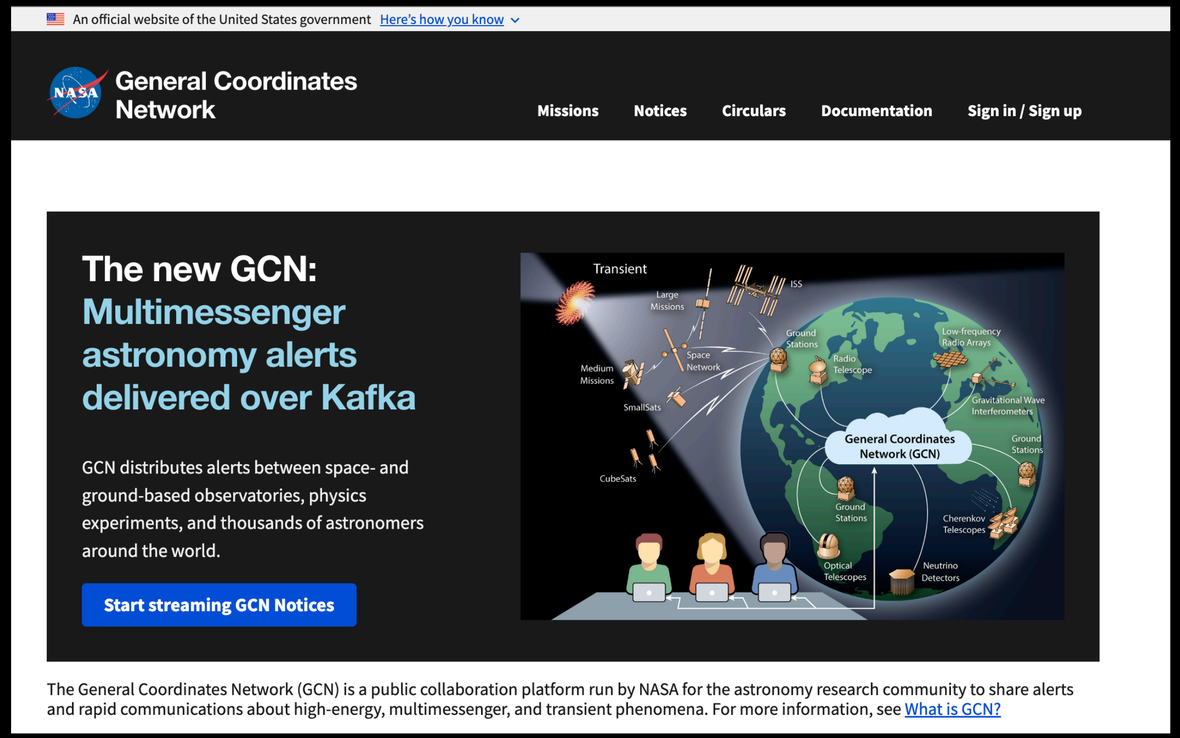
https://gcn.gsfc.nasa.gov/

- Current infrastructure relies largely on the NASA gamma-ray coordinates network.
- GCN notices and free-text circulars.
- Challenging for high alert rates, interpretation.
- Other networks (AMON) target multimessenger triggers.

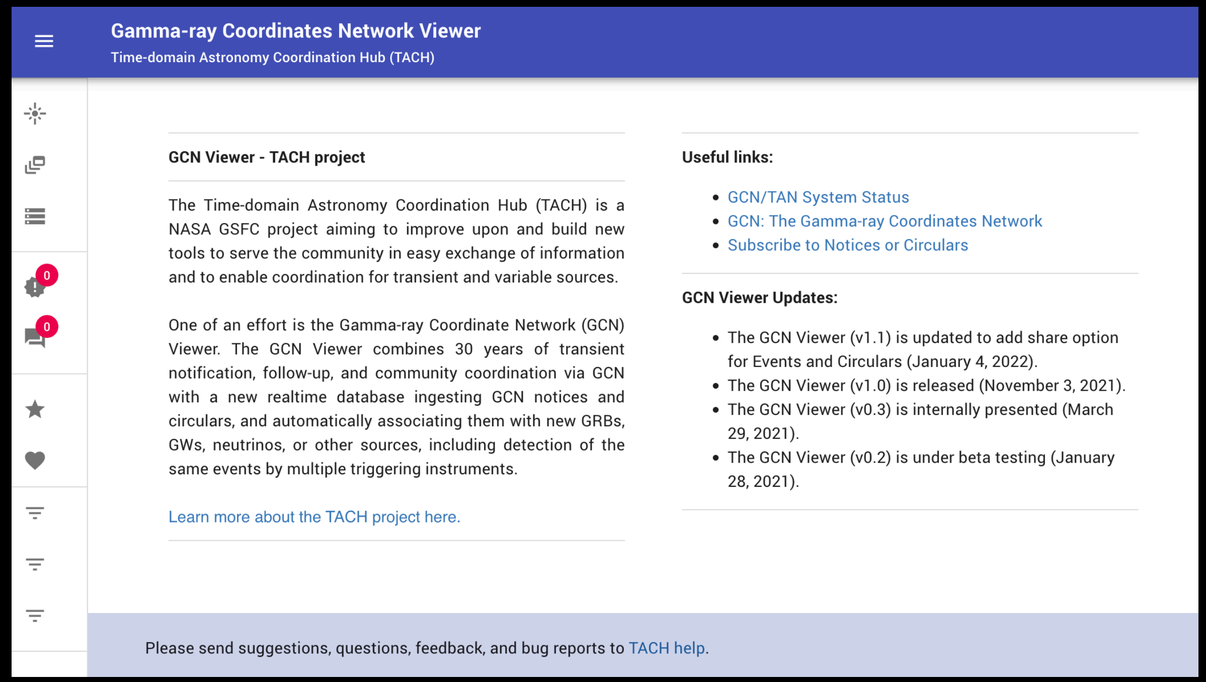
```
TITLE:   GCN CIRCULAR
NUMBER:  31839
SUBJECT: IceCube-220405A - IceCube observation of a high-energy neutrino candidate track-like event
DATE:    22/04/06 02:12:43 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@umd.edu>

The IceCube Collaboration (http://icecube.wisc.edu/) reports:

On 2022-04-05 at 22:20:03.41 UT IceCube detected a track-like event with a moderate probability of
being of astrophysical origin. The event was selected by the ICECUBE_Astrotrack_Bronze alert stream.
The average astrophysical neutrino purity for Bronze alerts is 30%. This alert has an estimated false
alarm rate of 2.02 events per year due to atmospheric backgrounds. The IceCube detector was in a
normal operating state at the time of detection.

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon_g_b/136506_15341152.amon),
more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 2022-04-05
Time:  22:20:03.41 UT
RA: 320.62 (+1.37, -1.13 deg  90% PSF containment) J2000
Dec: 29.06 (+0.94, -0.68 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical
source for the candidate neutrino.

There are no sources in the  4FGL-DR2 Fermi-LAT catalog in the 90% uncertainty region.  The nearest
source is 4FGL J2115.4+2932 (318.87 deg, 29.55 deg J2000, 1.82 deg away from the best-fit neutrino
position).

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic
South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at
roc@icecube.wisc.edu
```

NEW INFRASTRUCTURE

https://gcn.nasa.gov/



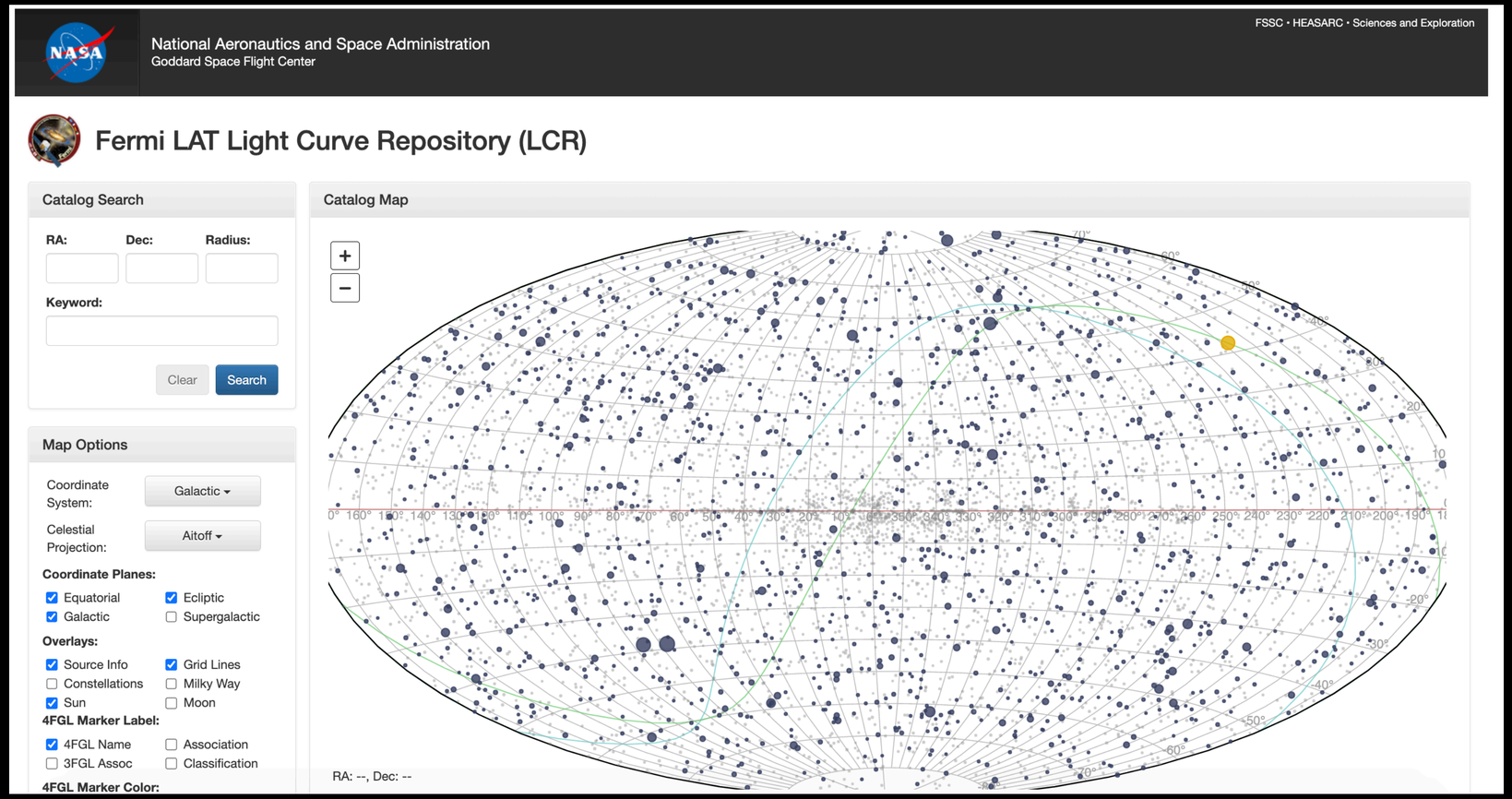
https://heasarc.gsfc.nasa.gov/wsgi-scripts/tach/gcn_v2/tach.wsgi/



- Higher alert rates and realtime correlation studies will require more flexible approaches to alert generation and distribution.
- **New GCN & TACH.** Streaming of notices, Kafka-based.

HIGH-LEVEL SCIENCE PRODUCT PIPELINES

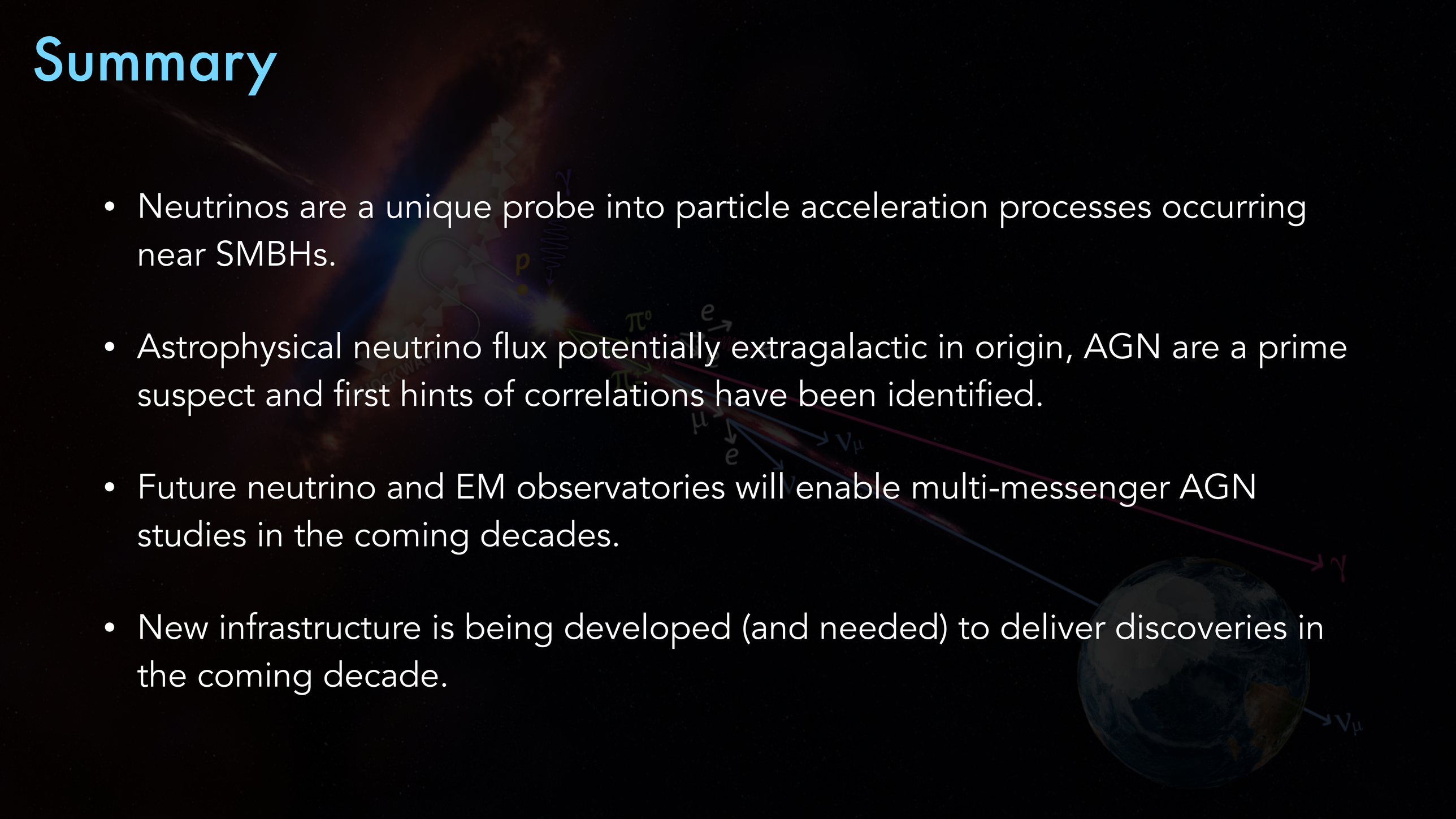
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/index.html



- The prompt identification of potential neutrino counterparts will require the automated generation of high-level science products.
- Integration / flexibility in the generation of alerts.

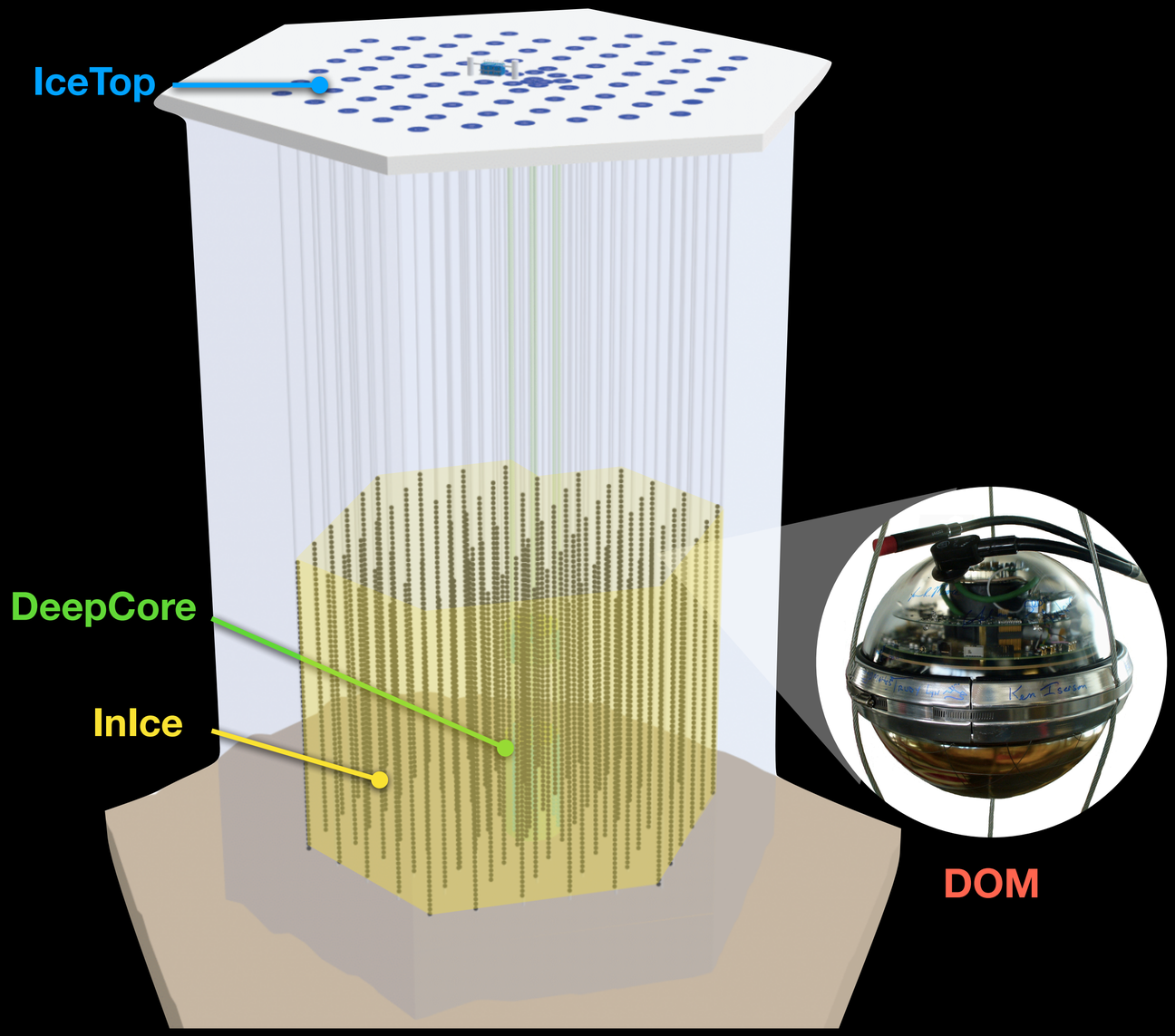
Summary

- Neutrinos are a unique probe into particle acceleration processes occurring near SMBHs.
- Astrophysical neutrino flux potentially extragalactic in origin, AGN are a prime suspect and first hints of correlations have been identified.
- Future neutrino and EM observatories will enable multi-messenger AGN studies in the coming decades.
- New infrastructure is being developed (and needed) to deliver discoveries in the coming decade.



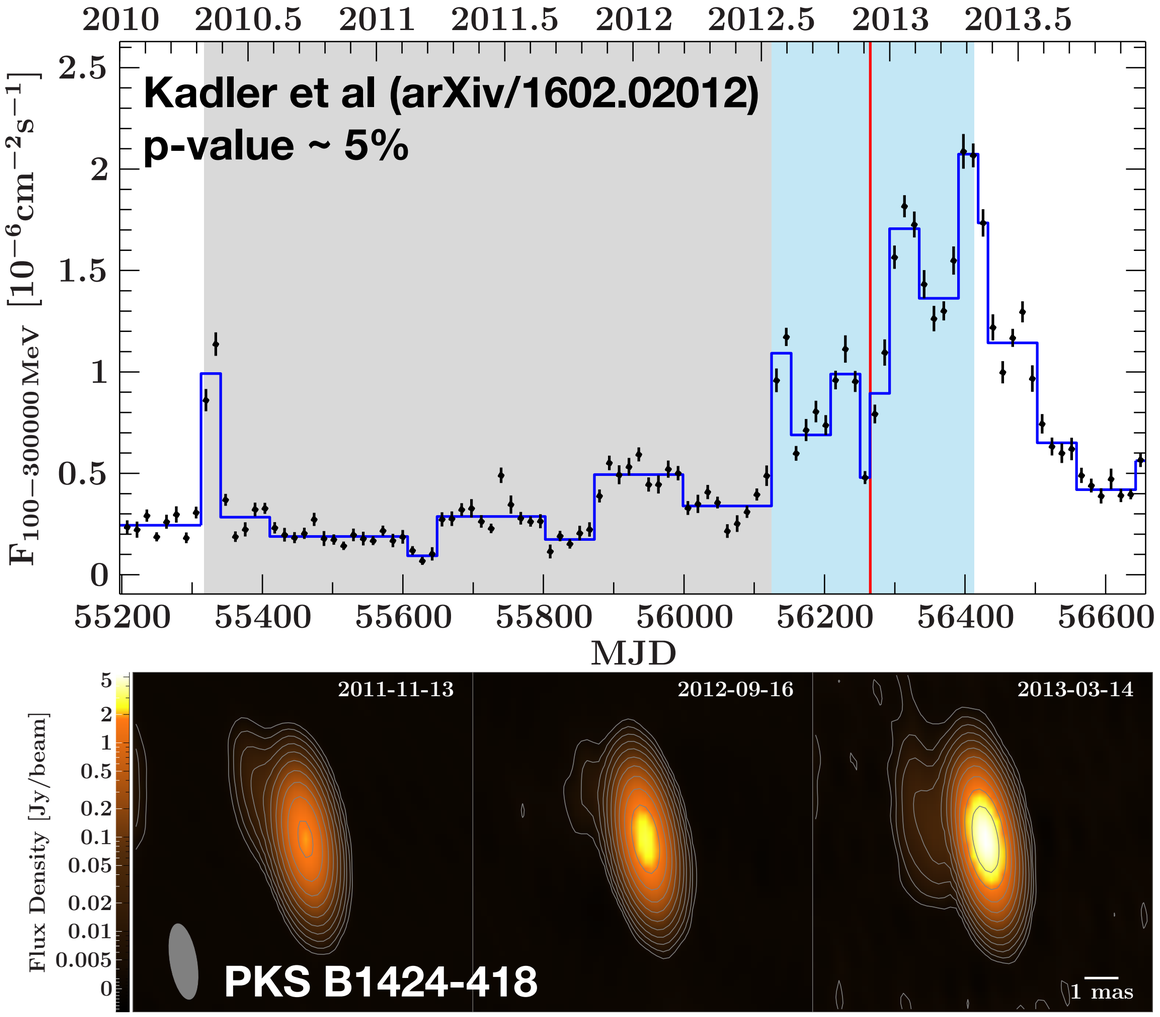
BACKUP

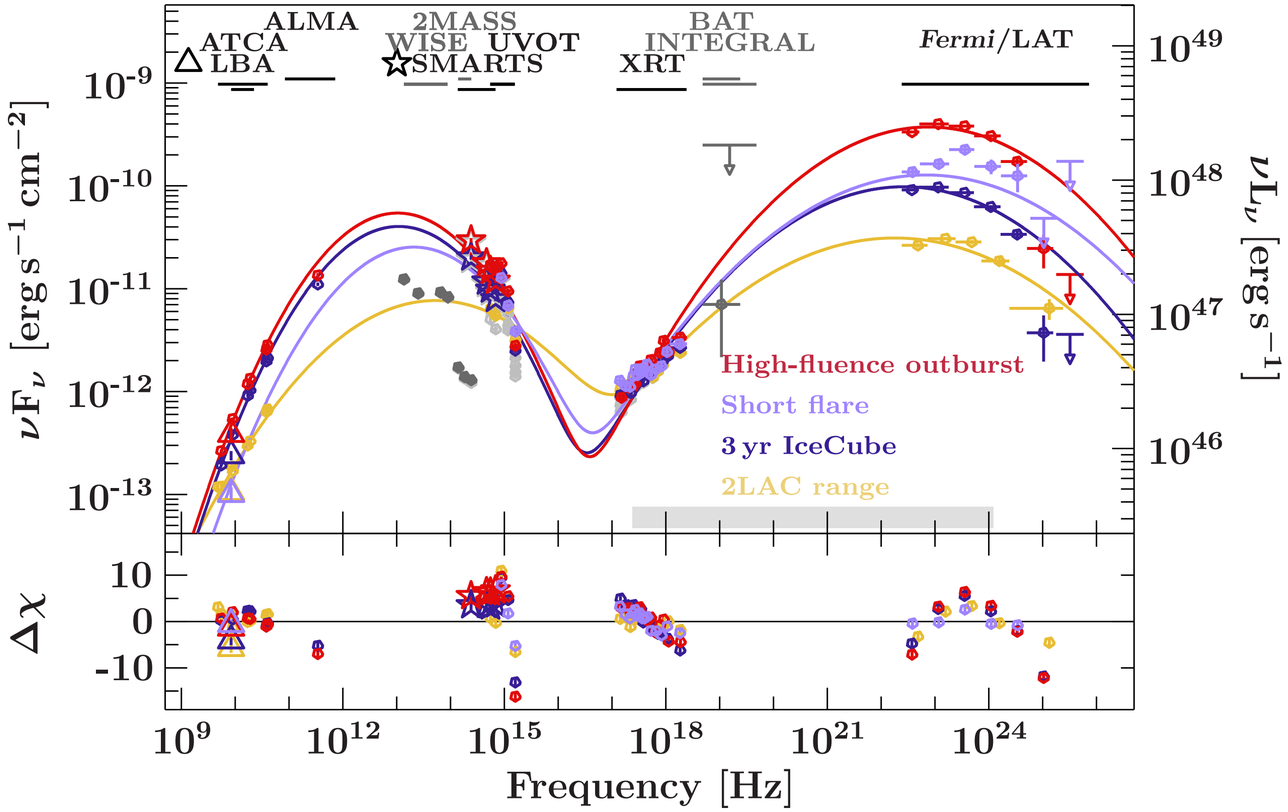
THE ICECUBE NEUTRINO OBSERVATORY



- **First km^3-scale neutrino detector**
- 5160 digital optical modules (DOMs) deployed at depths between ~1.5-2.5 km
- Construction finished in Dec 2010
- Surface air shower array (IceTop)
- Denser in-fill for O(10) GeV neutrinos (DeepCore)

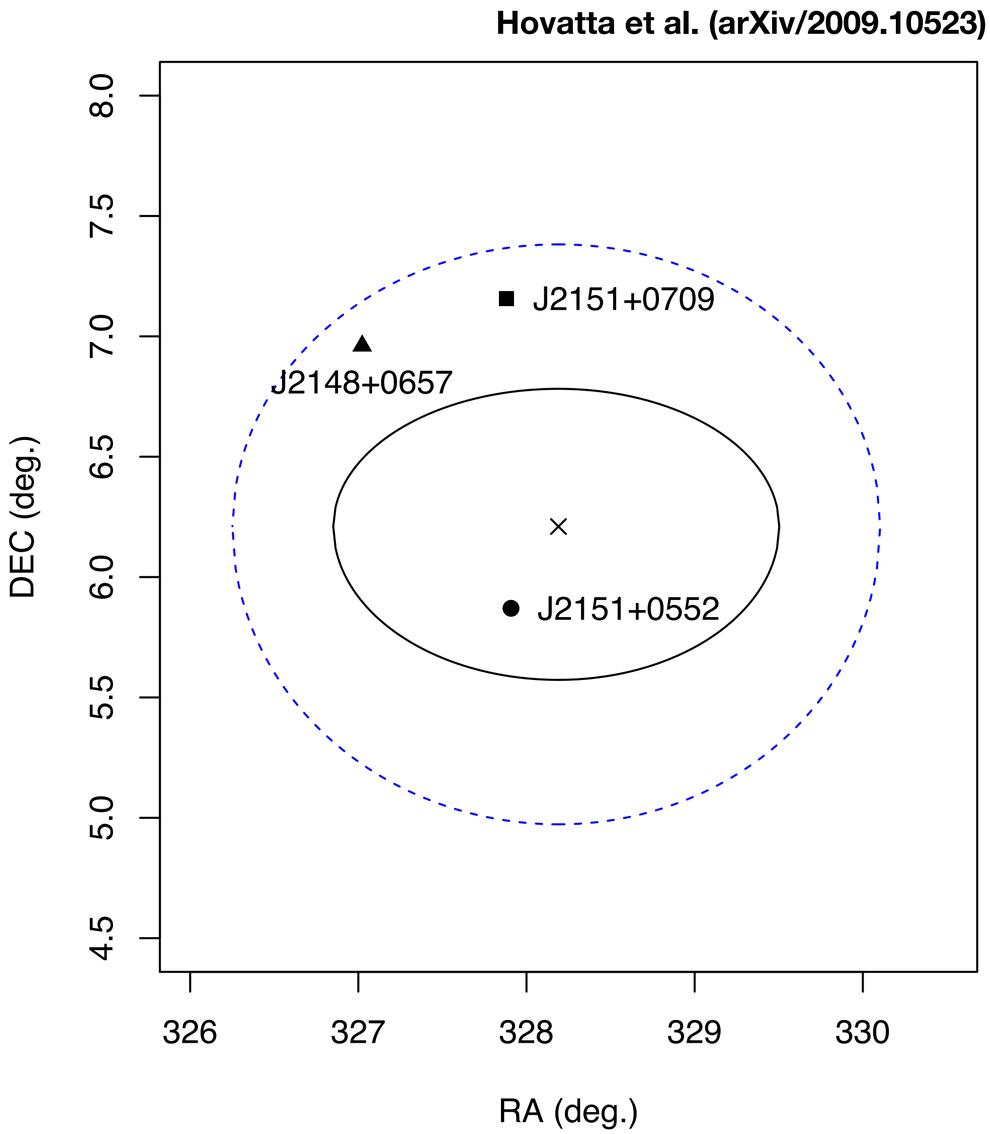
CORRELATION WITH MULTI-MESSENGER SIGNALS

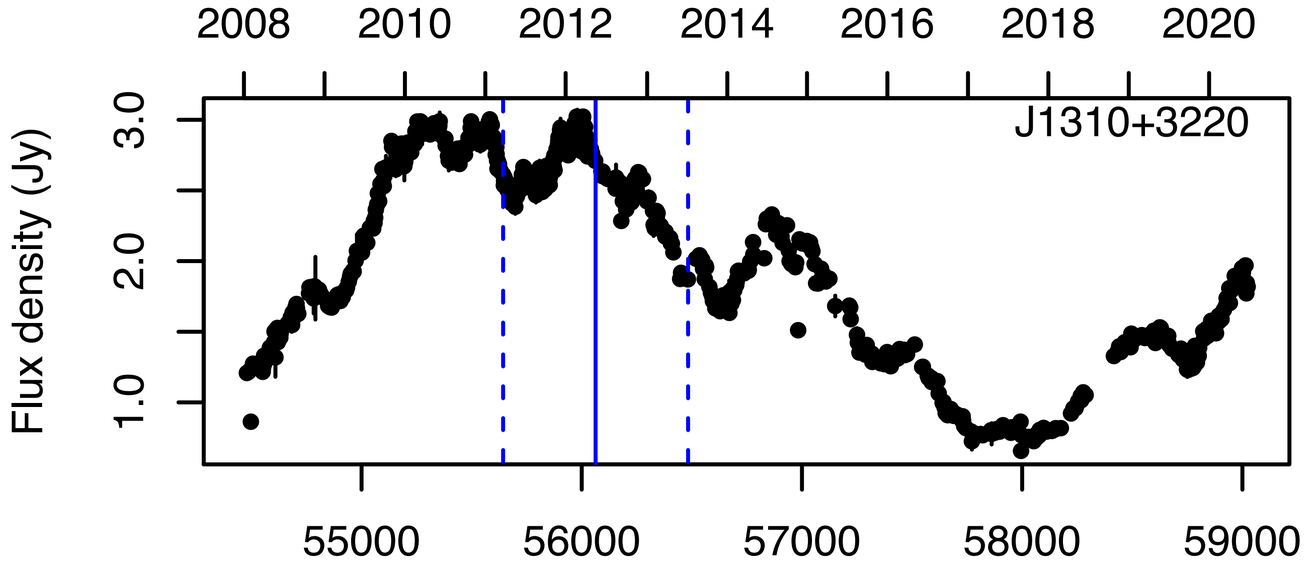




- Several claims from marginal significance correlations.
- E.g.: extreme blazars (Padovani et al. arXiv/1601.06550)

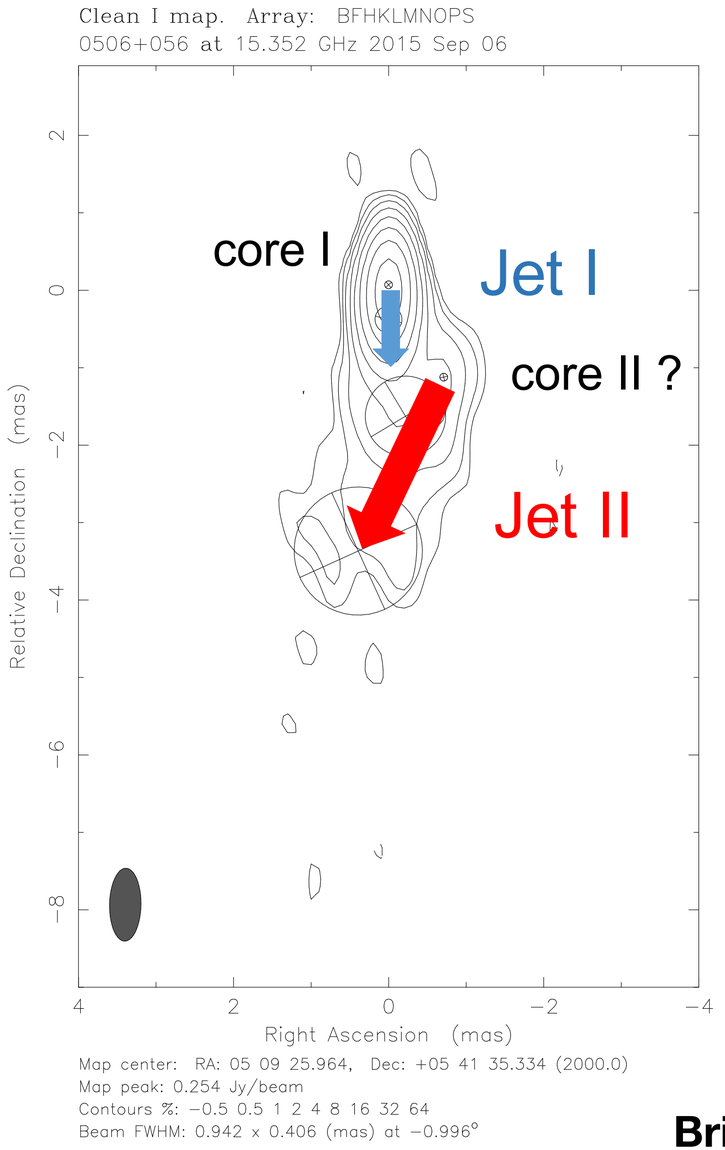
OVRO ASSOCIATIONS

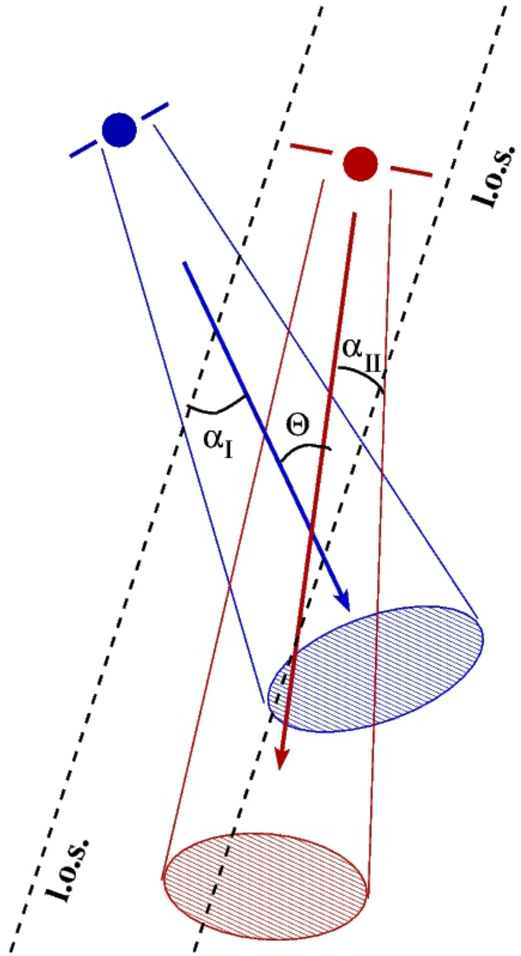




- No evidence for correlation in the OVRO sample (12-28% of the 57 neutrinos evaluated).
- Associations are mostly LSP FSRQs, although the sample is also dominated by that subclass.

A COSMIC COLLIDER?





Britzen et al. (A&A 630, A103, 2019)

- Point to unique jet kinematics of TXS 0506+056
- A few models are discussed:
  - Precessing inner jet.
  - Collision of jetted material.
  - Discovery of a binary AGN-jet on parsec scales?

Studying the AGN Radio and Neutrino correlation

A. Desai, J. Vandenbroucke, A. Pizzuto, R. Hussain and I. Safa
for the IceCube Collaboration

Neutrinos travel nearly unattenuated over cosmological distances making them an excellent messenger to study high-energy processes occurring in the universe. IceCube, the world's largest and most sensitive astrophysical neutrino detector, reported a high-energy neutrino event on 22 September 2017 which was found to be coincident with a flaring blazar, TXS 0506+056. This first multi-messenger observation hinted at blazars being sources of observed astrophysical neutrinos and raised a need for extensive correlation studies to properly understand which blazers might be neutrino sources. Here, we present a correlation analysis between 15GHz radio observations of active galactic nuclei reported in the MOJAVE XV catalog [1] and IceCube detector data and the sensitivity of this analysis to such a correlation.

Motivation:

- The Blazar PKS1502+106 was found to be possibly correlated with an IceCube alert (IC190730A). At the time of the alert, the radio observations of the FSRQ were seen reaching an all time peak flux of 4 Jy [2]
- Moreover, Radio neutrino correlation analysis will help us understand hadronic acceleration processes occurring in AGN [3].

Catalog and data description

- The MOJAVE XV dataset is used as the AGN source sample with radio observations. This sample consists of 5321 observations of 437 AGNs in the 15 GHz band, obtained between 1996 January 19 and 2016 December 26 with the VLBA in full polarization mode.
- IceCube data with full sky coverage detected between 2008 to 2017 is used. We look for spatial correlations in the directions of the ra,dec positions of the MOJAVE sources for the analysis.

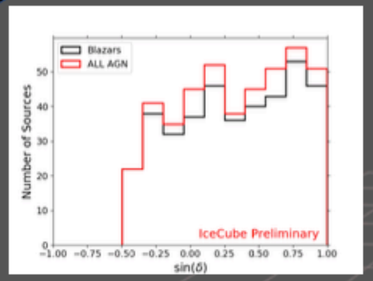


Fig 1: Distribution of the MOJAVE source sample (complete sample and only blazars)

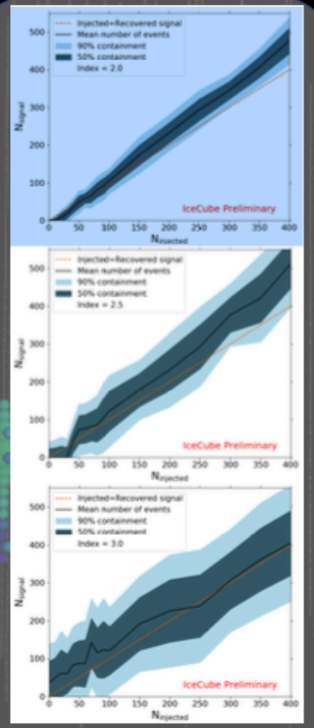


Fig 2: Ability of the analysis to reconstruct a signal from the MOJAVE AGN is shown for different spectral assumptions. X-axis denotes the number of signal events in the sample injected on top of background, while y-axis denotes the number of fit signal events for each of these spectral assumptions.

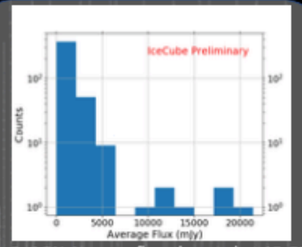


Fig 3: AGN Average flux observed at 15 GHz used as the weights for the stacking analysis

Likelihood stacking description:

- A time independent stacking analysis is used to test the hypothesis where the neutrino flux is proportional to the radio flux $F_\nu \propto F_R$
- We make use of the average radio flux of each source as the weight to be used in stacking; $w_i = F_{Ri}$ (see Figure.3)
- The muon neutrino flux obtained from the stacking with 90% C.L. (Confidence Limit) gives us the sensitivity of the correlation hypothesis test.

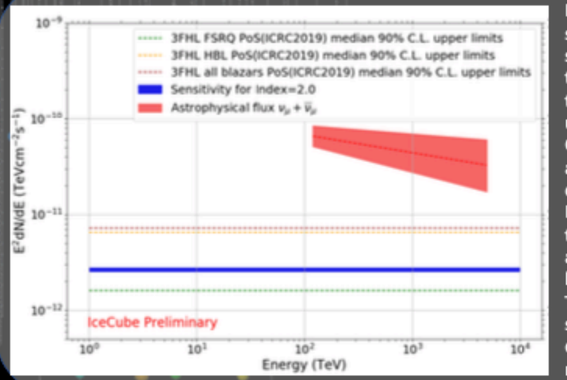


Fig 4: The preliminary sensitivity results for a spectral index of 2 for this work is shown as the blue line. The upper limits (at 90% C.L.) from a separate analysis testing the correlation between IceCube events and the 3FHL sample [4] are shown in dashed lines for comparison. The red shaded region shows the measured diffuse astrophysical neutrino flux from [5].

References:

[1] Lister, M.L. et.al, 2018ApJS..234...12L
[2] S. Kiehlmann et.al. ATel. 12996, 1 (2019)
[3] Plavin, A.V. et.al. arXiv:2001.00930
[4] IceCube Collaboration, PoS ICRC2019 (2020) 916
[5] IceCube Collaboration, , PoS(ICRC2017)1005

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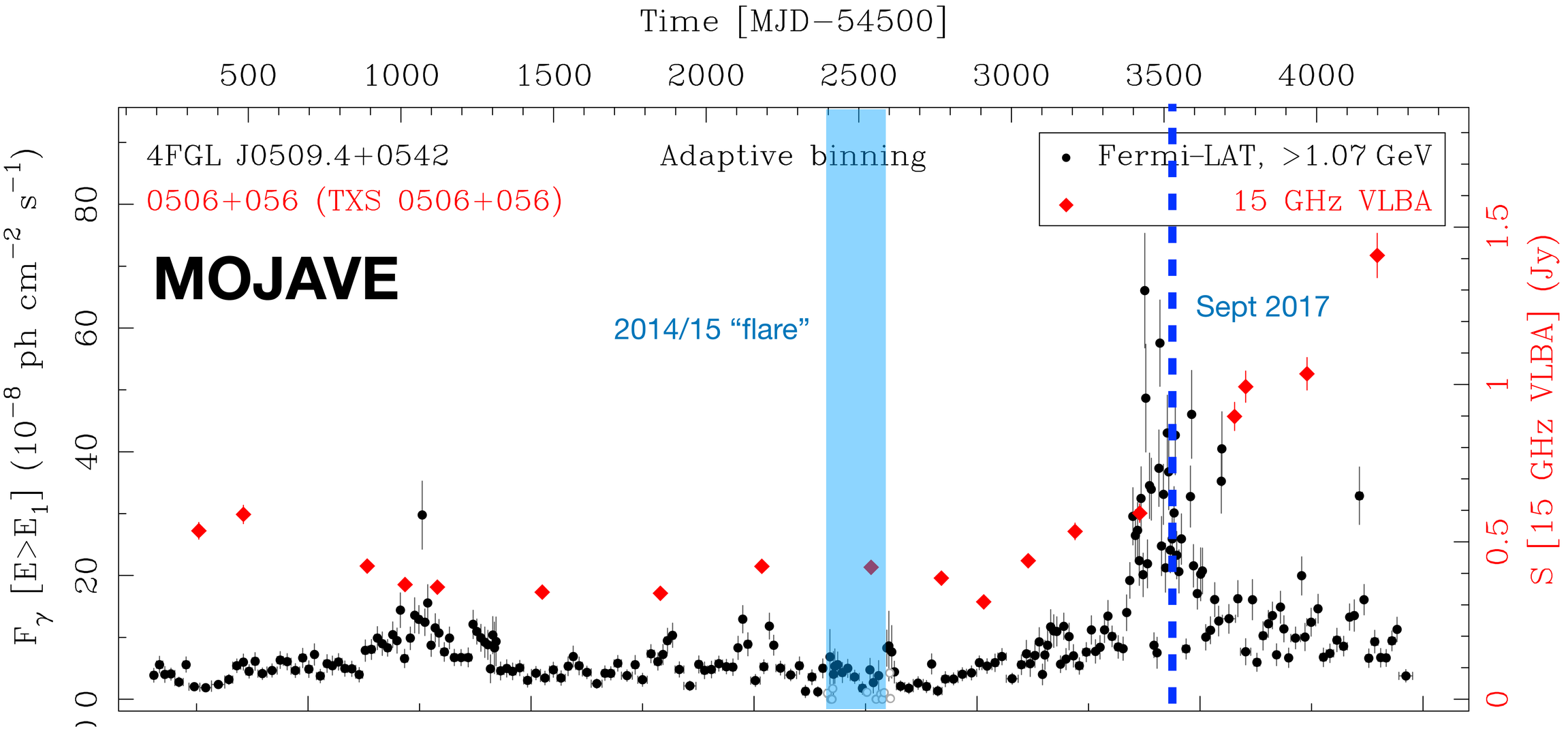
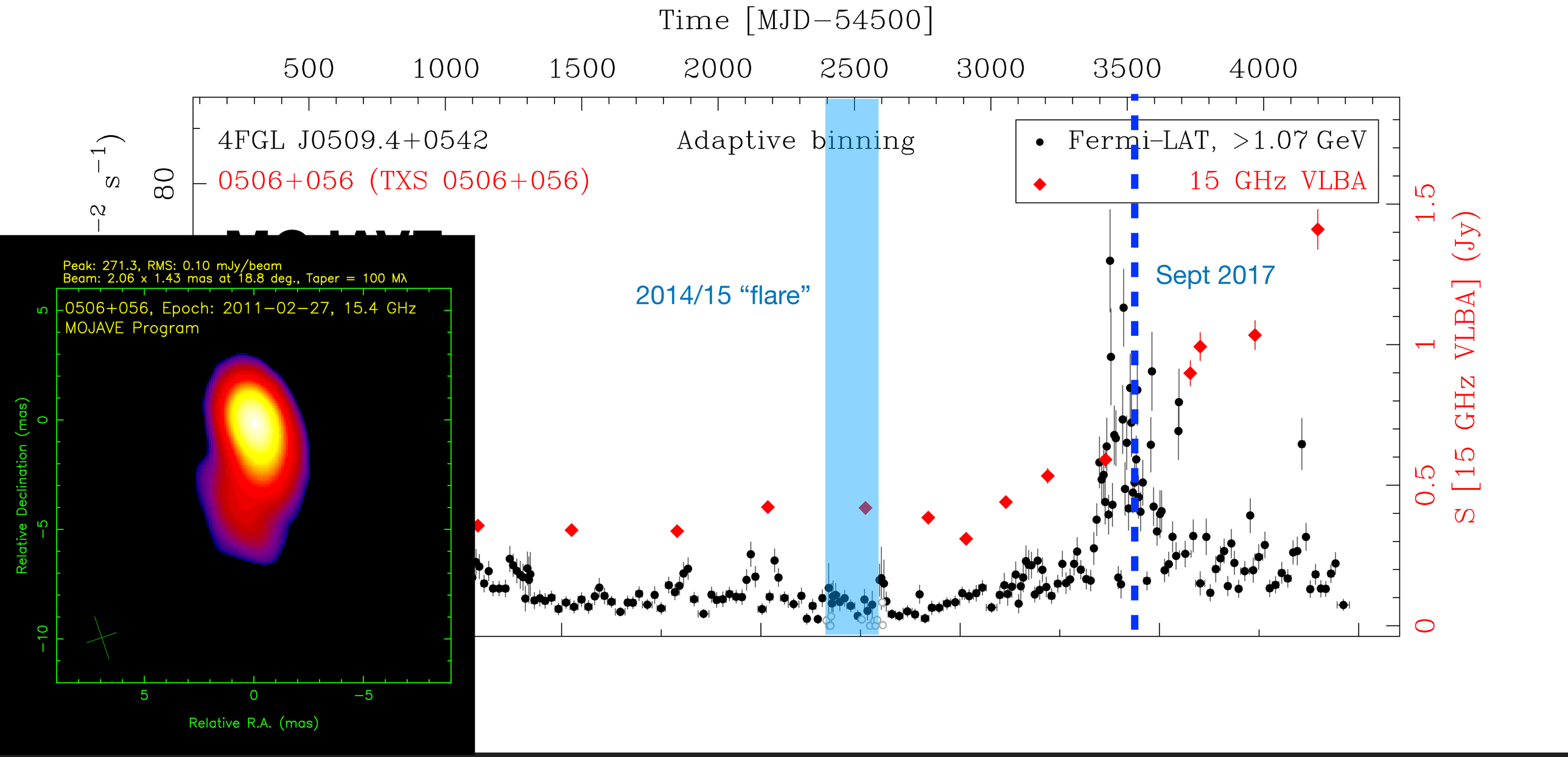
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-305.pdf

A SIGNAL IN RADIO?

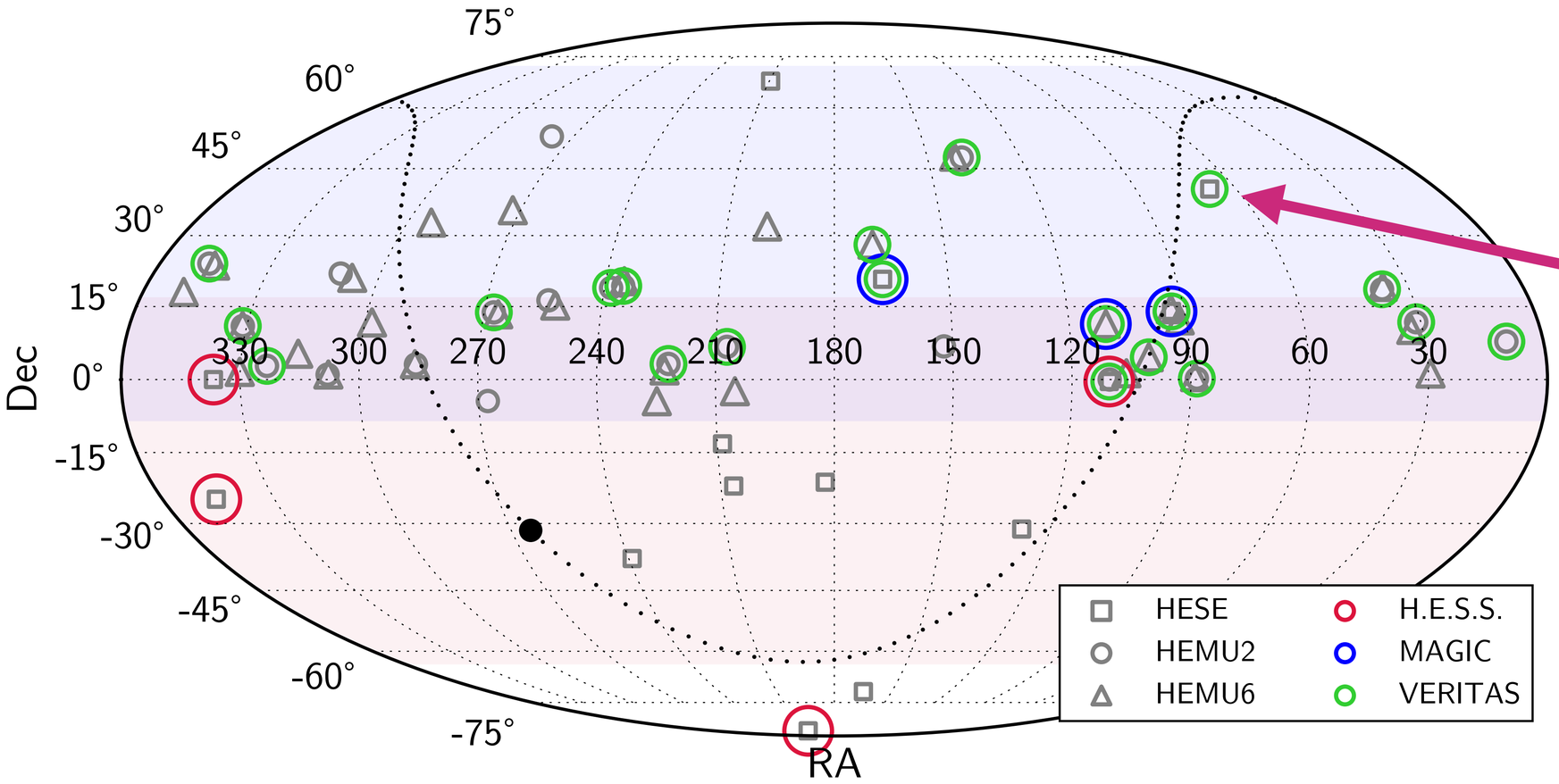


A SIGNAL IN RADIO?

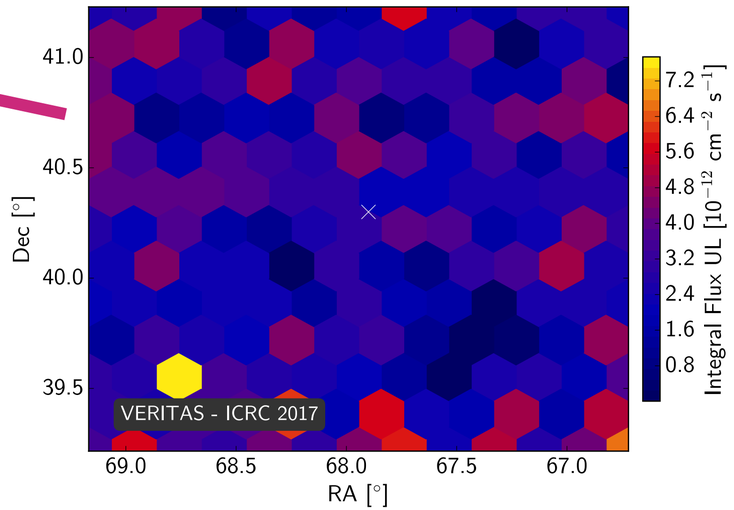


CORRELATIONS WITH MULTI-MESSENGER SIGNALS

Santander et al.
arXiv/1708.08945



VHE gamma-ray follow-ups



- Multiple observational programs aimed at identifying EM counterparts to high-energy neutrino events.
- Dedicated gamma-ray follow-up program from IceCube + IACTs.